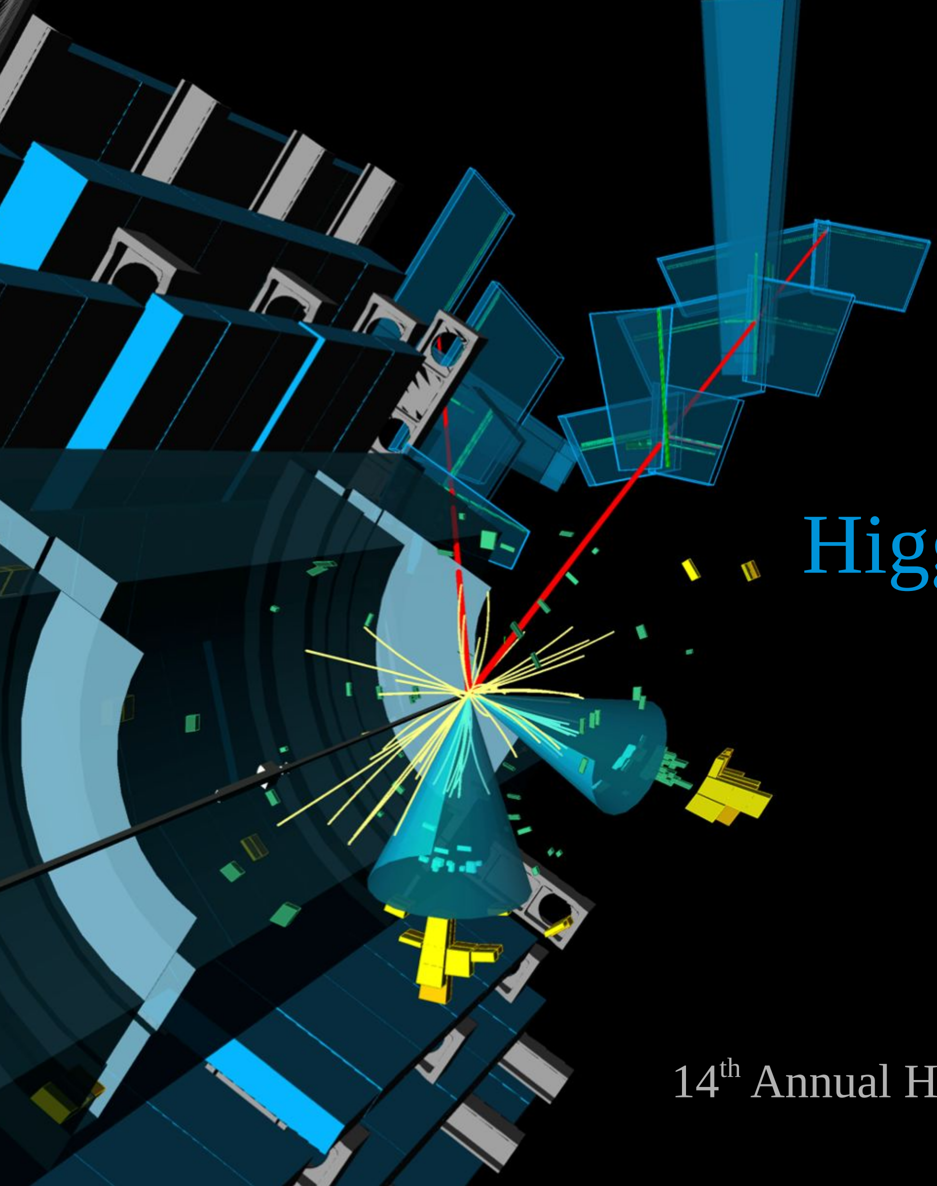


Search for the Higgs boson decay to charm quarks at the ATLAS experiment

Hannah Arnold (Nikhef)

14th Annual Helmholtz Alliance Workshop on "Physics at the Terascale"
November 23, 2021

Motivation

- **Yukawa couplings** - the couplings of the Higgs boson to quarks and charged leptons – are one potential source of **fermion masses**

- Prediction: $\boldsymbol{y_f \sim m_f}$

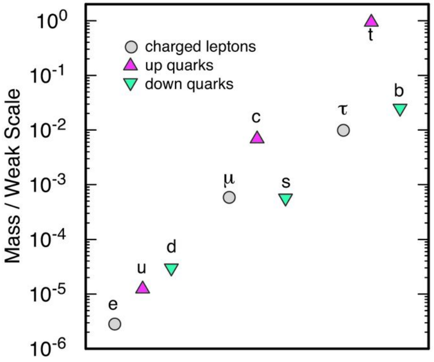
- **Observed for 3rd generation fermions, evidence for 2nd generation leptons**

- Yukawa couplings provide *no fundamental insight into the fermion mass hierarchy* – masses span orders of magnitude

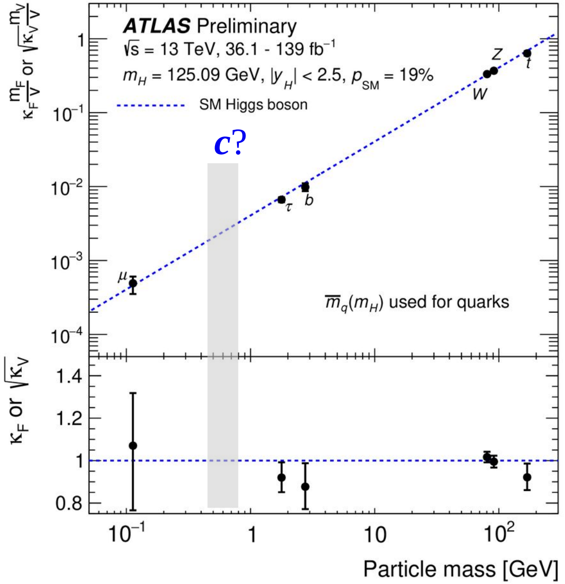
  ⇒ Need BSM physics to explain

⇒ Establishing and measuring the couplings of the Higgs boson with *all* fermions is a top priority

Next in line: Higgs-charm coupling – (only viable?) probe for 2nd-generation quarks Yukawa coupling



Chris Quigg, arXiv:0905.3187

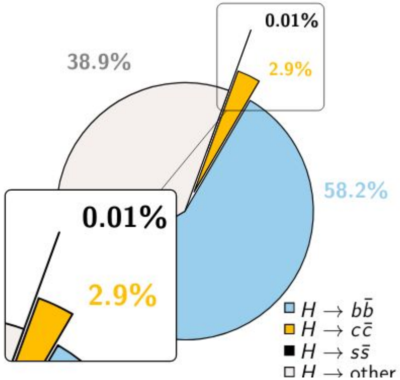


ATLAS-CONF-2021-053

Introduction: *VH, H → cc*

H → cc - unique opportunity to directly probe and constrain the Higgs-charm coupling

- Largest contribution to the Higgs total width that we don't have evidence for yet
- Experimentally challenging:
  - ***c*-tagging**
  - ***V(=W/Z)H* production and *V(→leptons)*** for (multijet) background suppression and triggering



From A. Chisholm @Higgs Hunting 2021

VH, H → cc results

- **2021: ATLAS analysis on the full Run-2 dataset (139 fb^{-1})** [ATLAS-CONF-2021-021] ⇒ **focus of this talk**
- 2019: CMS search on partial Run-2 dataset (36 fb^{-1}) [JHEP 03 (2020) 131]
  - Obs. (exp.) upper limit on σ×BR @ 95% C.L.: **70 (36) × SM prediction**
- 2018: ATLAS *Z(→ll)H(→cc)* search on partial Run-2 dataset (36 fb^{-1}) [PRL 120 (2018) 211802]
  - Obs. (exp.) upper limit on σ×BR @ 95% C.L.: **110 (150) × SM prediction**

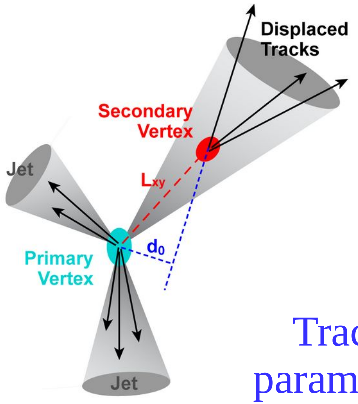
c-tagging

- identification of jets that likely contain a c-hadron

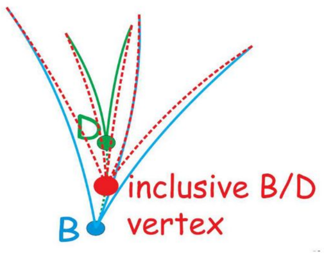
Current *c*-tagging strategy:

- Rely on the "low-level" **algorithms** developed for ***b*-tagging**
- The "high-level" algorithms - that combine the low-level tagger output into final discriminants using multivariate analysis techniques – are used to identify ***c*-jets as signal** and *b*- and light-jets as background

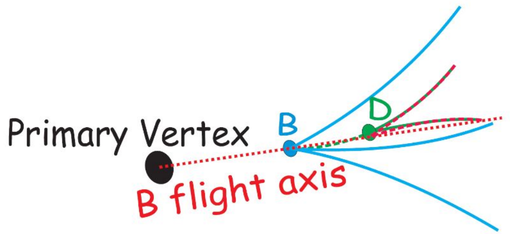
Selection of "low-level" *b*-tagging algorithms



IP3D
Track impact-parameter based



SV1
inclusive 2nd / 3rd vertex reconstruction



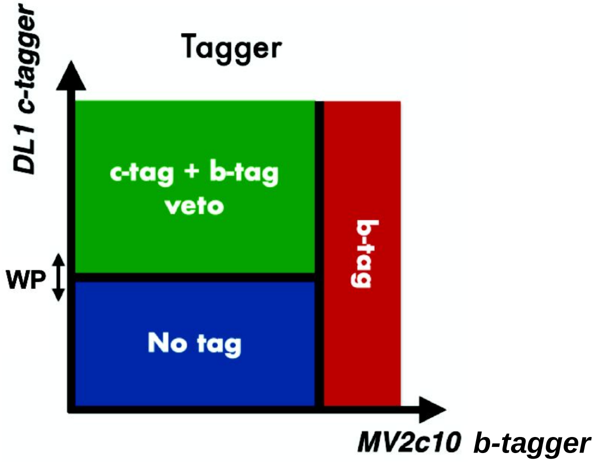
JetFitter
b- → *c*-hadron decay chain reconstruction

…

Source: D0 collaboration

2008 J. Phys.: Conf. Ser. 119 032032

Courtesy of M. Stamenkovic



Dedicated 2D tagging strategy:

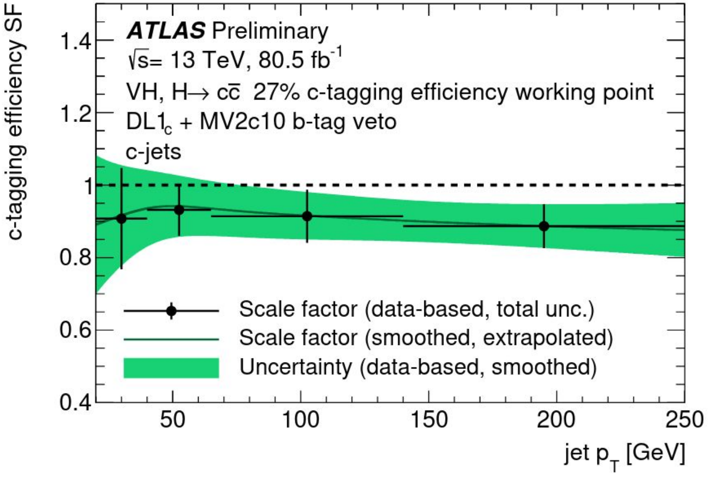
i. Including b-tag veto $\to$ orthogonality with $VH(\to bb) \Rightarrow$ combination?

ii. Optimised for $VH(\to cc)$ limit

Average performance (on ttbar)

c-jets	*b*-jets	Light jets
27%	8%	1.6%

For comparison: a typical b-tagging algorithm achieves a b-jet efficiency of ~70% for similar c-/light jet mistag efficiencies



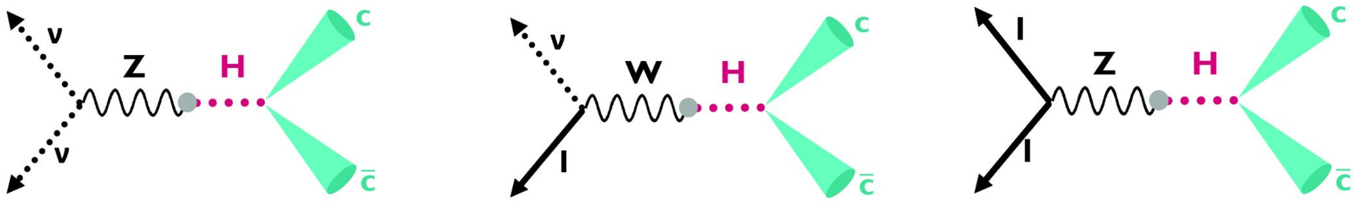
⇐ Dedicated calibration for c-, b- and light jets using "standard" b-tagging calibration methods(*) - uncertainties: **at most 15%**

(*) Eur. Phys. J. C79(2019) 970, ATLAS-CONF-2018-001, ATLAS-CONF-2018-006

$VH(\rightarrow cc)$ analysis strategy

Nikhef

Three lepton channels: 0/1/2L - according to number of reconstructed electrons/muons

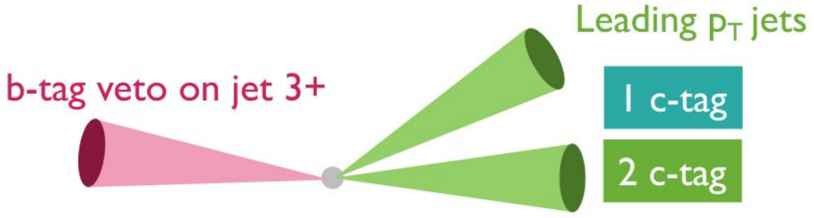


Courtesy of M. Mironova

⇒ electrons, muons and/or missing transverse momentum (Etmiss)

Cut-based analysis with m(jj) as final discriminant

- m(jj): invariant mass of the two p_T-leading jets



Courtesy of M. Mironova

1 and 2 c-tag categories

- c-tag includes b-veto
- b-tag veto on additional jets

⇒ Orthogonality to $VH(\rightarrow bb)$

Further categorisation: $p_T(V)$ and # of jets ⇒ isolate regions with better $S/(\sqrt{})B$

$VH(\rightarrow cc)$ analysis strategy II

Background estimate

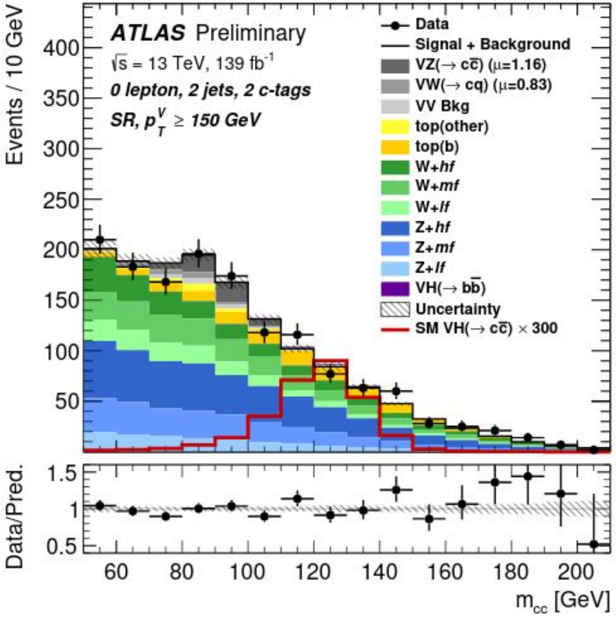
- **From *simulated samples***
  exception: multijet contribution in 1L (negligible in 0/2L (after selection))

- ***Truth-flavour tagging*** $\Rightarrow$ maximise the statistical power
  weight events with the tagging (in-)efficiency of the Higgs-candidate jets

- **Systematic uncertainties** from comparisons to alternative samples

- **Various control regions in data**
  $\Rightarrow$ determine **normalisation** and constrain modelling uncertainties

0-lepton channel



Large and diverse background contributions:
Z+jets, W+jets, top

Signal extraction – 3 POI fit

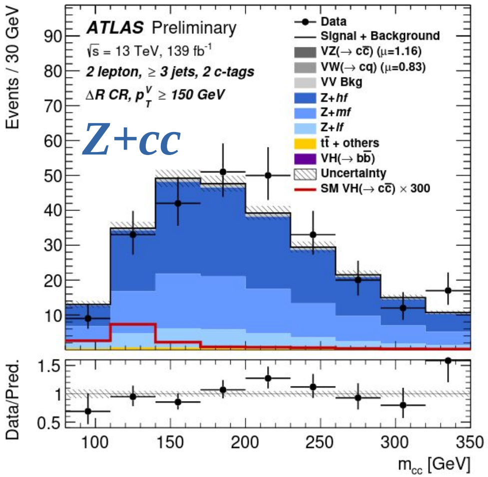
Binned profile likelihood fit in m(jj) simultaneously in 42 regions

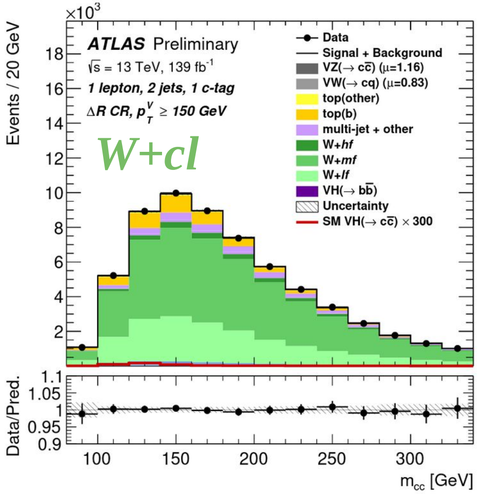
- $VH(\rightarrow cc)$
- $VW(\rightarrow cl)$
- $VZ(\rightarrow cc)$

} **cross-check signals** $\Rightarrow$ **validate analysis strategy**

Control regions

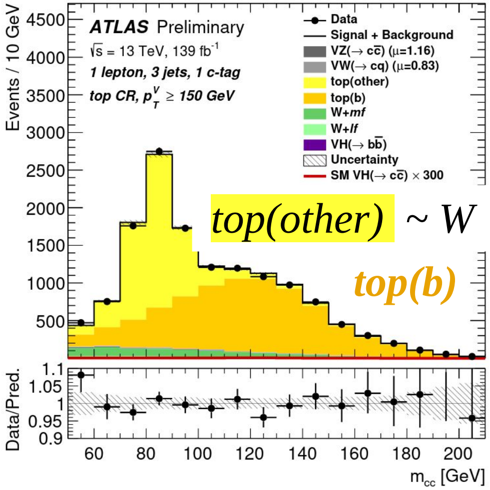
V+jets background (*V* = *W*, *Z*)



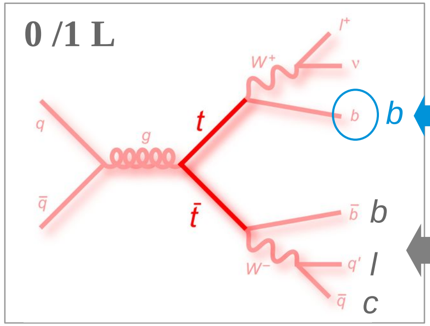


- **1 / 2 c-tag "high-ΔR"** ⇑
  - ΔR < 1.2-2.2 ⇒ SR
  - 1.2-2.2 < ΔR < 2.5 ⇒ CR
- **0 c-tag "SR"** - norm-only

Top background



- 0 /1L:
  1 *c*-tag
  + *inverted b*-tag veto on 3rd jet
  =
  1 *c*-tag
  + *b*-tag on 3rd jet
  ⇐
- 2L: *eμ* CR



Suppressed in SR, enriched in CR

Higgs candidate

Summary: analysis regions

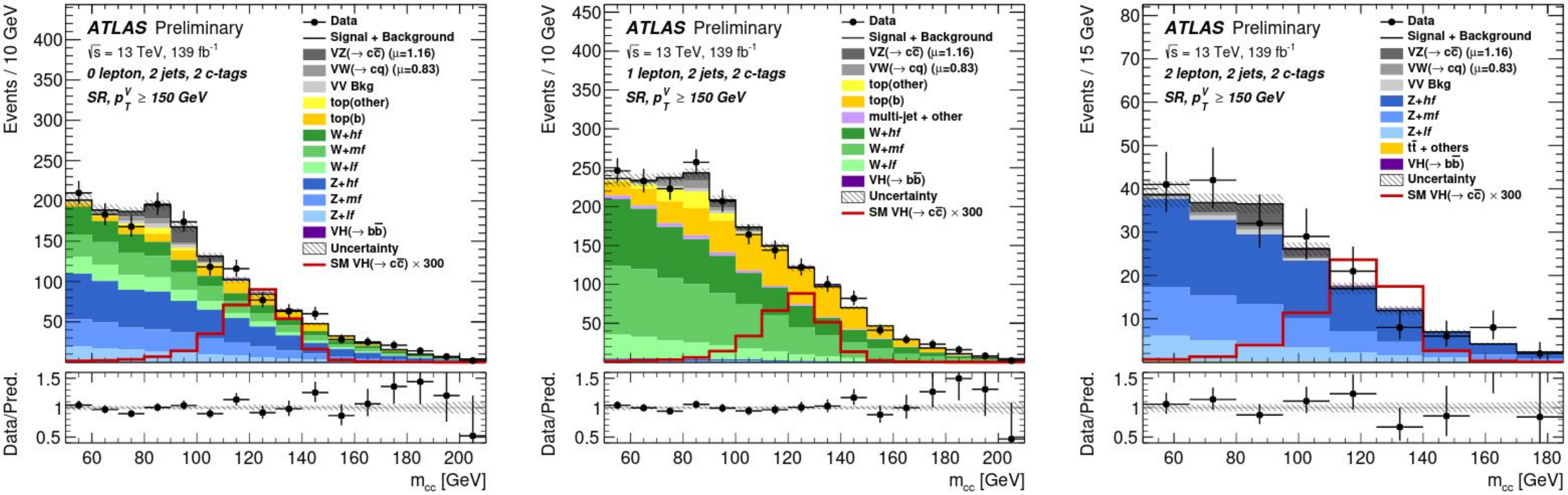
Courtesy of M. Mironova

16 Signal Regions

28 Control Regions

		ΔRcc < ΔRcc selection				ΔRcc selection < ΔRcc < 2.5	
		0 c-tag CR	SR		Top CR	ΔRcc CR	
0L	pTV > 150 GeV		1 c-tag 2 jet	2 c-tag 2 jet		1 c-tag 2 jet	2 c-tag 2 jet
			1 c-tag 3 jet	2 c-tag 3 jet	1 c-tag 3 jet	1 c-tag 3 jet	2 c-tag 3 jet
1L	pTV > 150 GeV	0 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet		1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag 3 jet	1 c-tag 3 jet	2 c-tag 3 jet	1 c-tag 3 jet	1 c-tag 3 jet	2 c-tag 3 jet
2L	75 < pTV < 150 GeV	0 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet	1 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet	1 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet
	pTV > 150 GeV	0 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet	1 c-tag 2 jet	1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet	1 c-tag 3+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet
		Norm-only			Norm-only		

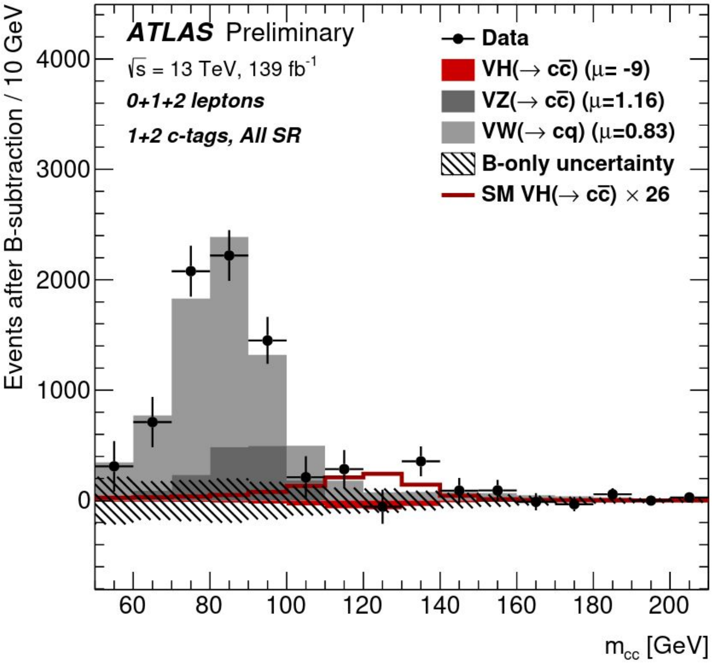
Post-fit m(cc) distributions



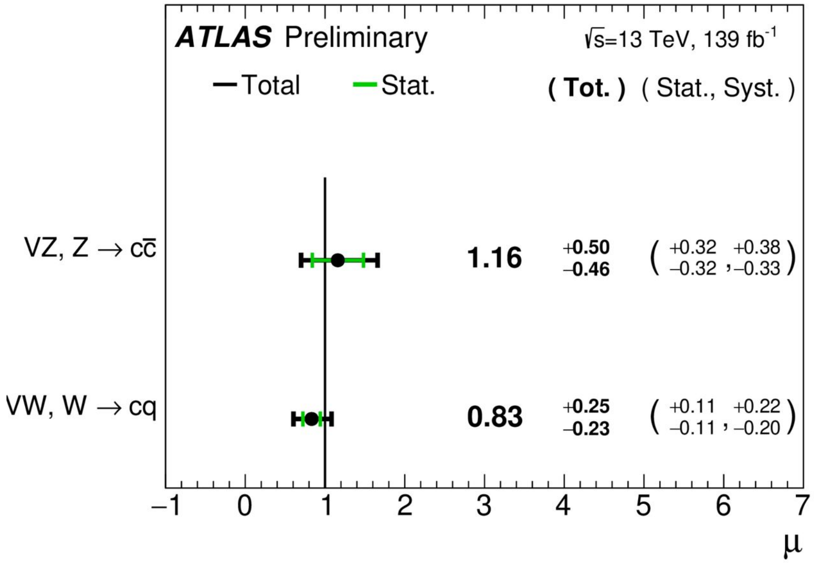
Most sensitive signal region in each channel: 2 *c*-tag, 2 jet, $p_T(V) > 150$ GeV

Expected signal × 300

Results: signal strengths



Signal strength $\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}}$



Obs. (exp.) significance:

2.6 (2.2) σ

3.8 (4.6) σ

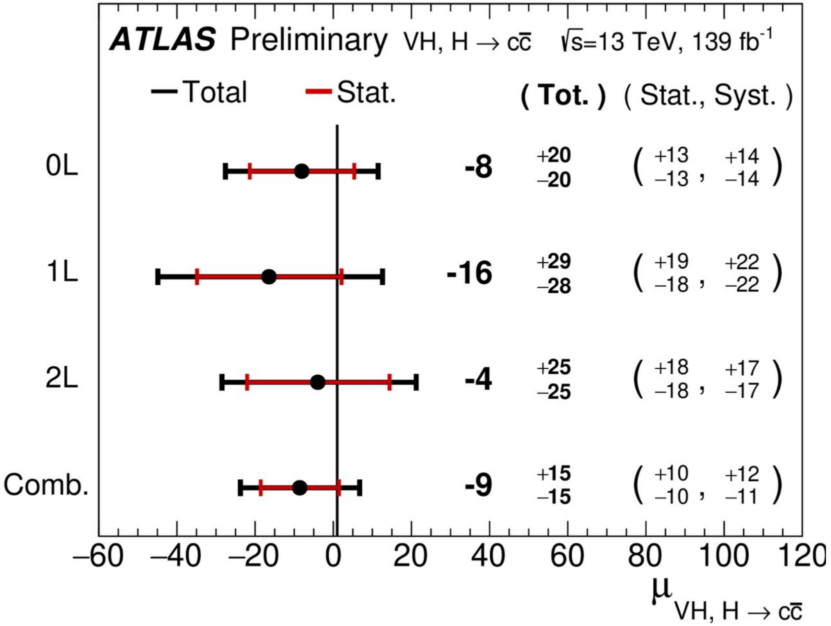
$\boldsymbol{\mu_{V(H \to cc)}}$ **= -9 ± 10 (stat.) ± 12 (syst.)**

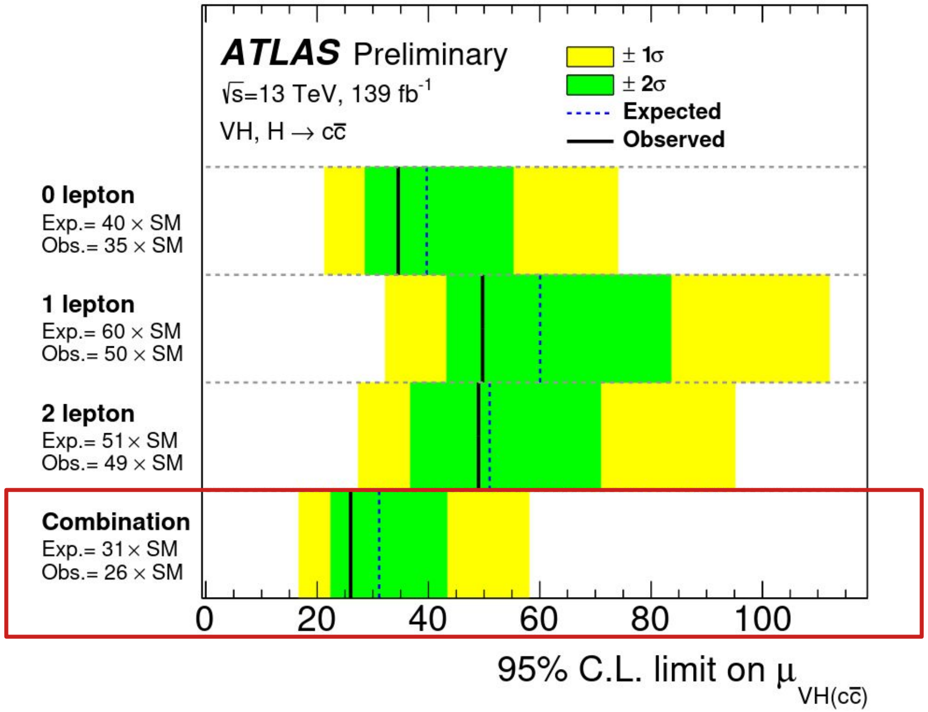
Compatibility with the SM: 84%

First “measurement” of VW/VZ using *c*-tagging

Good agreement with SM prediction
⇒ validation of $VH(\to cc)$ search strategy

More $VH(\rightarrow cc)$ results





Individual channel results from POI decorrelation (i.e. otherwise fit model unchanged)

Most stringent limit on $H \rightarrow cc$ to date!

- Good agreement between channels
- 0L most sensitive channel (high stat. + bkg. Control from 1/2L)

Uncertainties breakdown

Source of uncertainty		$\mu_{VH(c\bar{c})}$
Total		15.3
Statistical		10.0
Systematics		11.5
Statistical uncertainties		
Data statistics only		7.8
Floating normalisations		5.1
Theoretical and modelling uncertainties		
$VH(\rightarrow c\bar{c})$		2.1
Z+jets		7.0
Top-quark		3.9
W+jets		3.0
Diboson		1.0
$VH(\rightarrow b\bar{b})$		0.8
Multi-Jet		1.0
Simulation statistics		4.2
Experimental uncertainties		
Jets		2.8
Leptons		0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.2
Pile-up and luminosity		0.3
Flavour tagging	c-jets	1.6
	b-jets	1.1
	light-jets	0.4
	τ-jets	0.3
Truth-flavour tagging	ΔR correction	3.3
	Residual non-closure	1.7

Statistical and systematic uncertainties are of the same order

Uncertainties on the free-floating background normalisations are considered statistical unc.

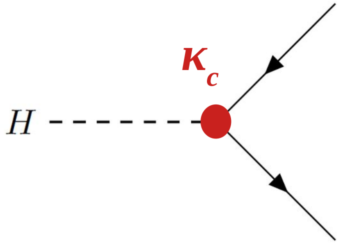
Dominant systematic uncertainty: *Z*+jets modelling

Followed by uncertainties related to the **limited simulated sample sizes**

Interpretation of the result

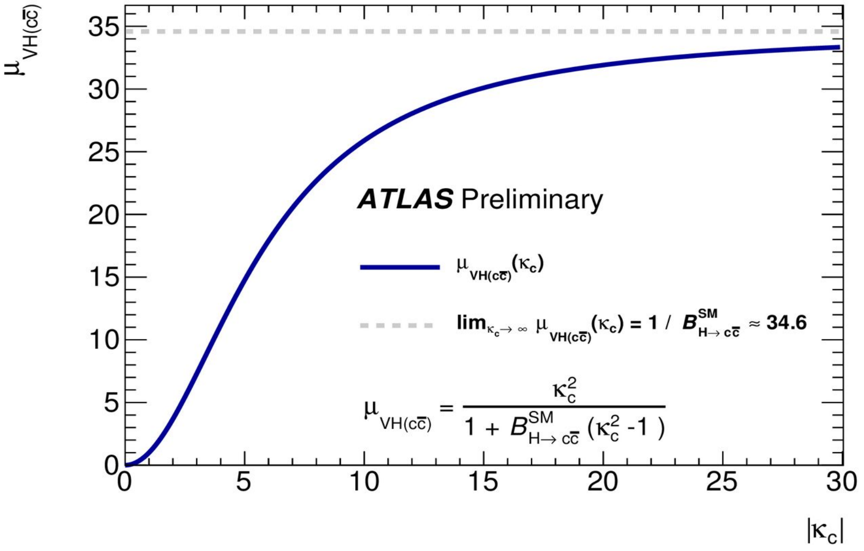
CERN-2013-004 (2013)

κ framework ⇒ study potential BSM modifications of the Higgs-boson coupling *strength*



Higgs-charm coupling modifier

$\kappa_c = 1$ in SM



Assumptions:

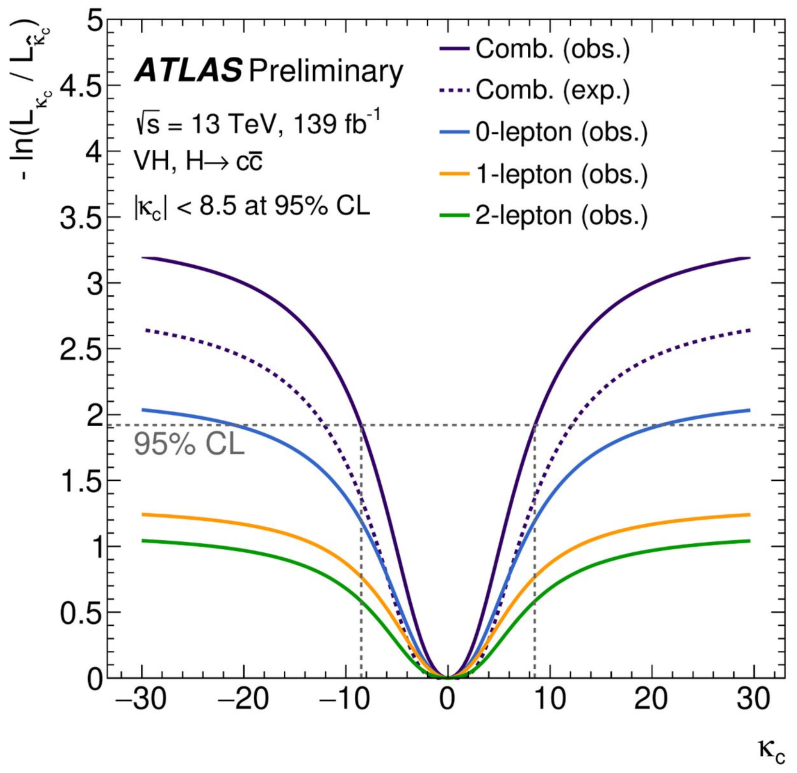
- Modifications of the *partial decay width* by κ_c^2
- Modifications to the *total Higgs-boson total width*, assuming
  - Only decays to SM particles
  - All other coupling-strength modifiers are 1

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

Parametrisation

Neglect modifications to the production because no ggZH parametrisation incl. κ_c is available

$VH(\rightarrow cc)$: κ_c constraint



Best fit value: $\kappa_c = 0$ (because of negative $\mu_{V(H\rightarrow cc)}$)

First direct constraint on κ_c!

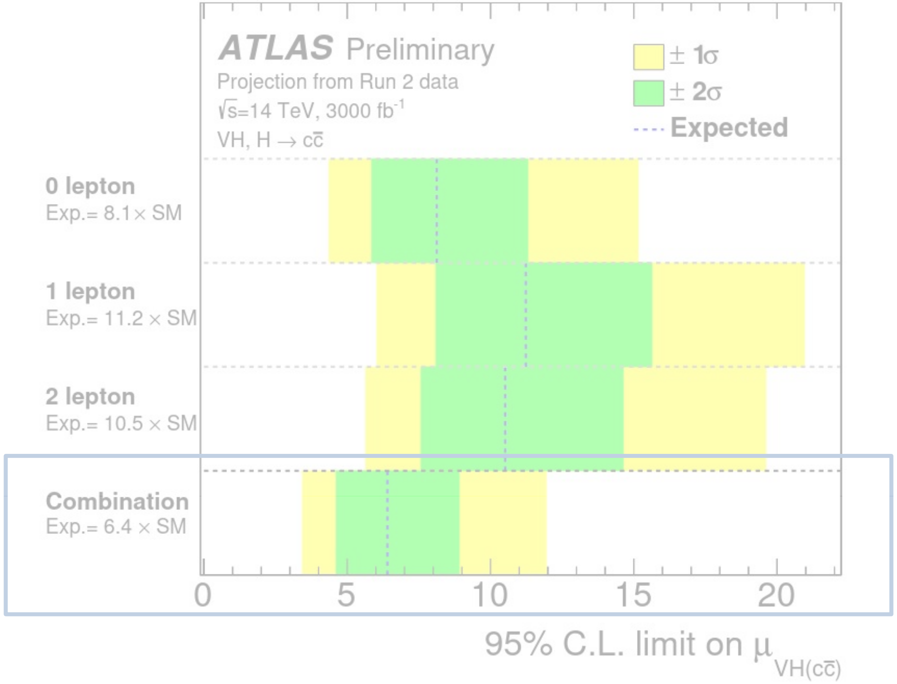
@68% CL: $|\kappa_c| < 3.5$ (4.9) obs. (exp.)

@95% CL: $|\kappa_c| < 8.5$ (12.3) obs. (exp.)

Prospects: $VH(\rightarrow cc)$ @ the HL-LHC

ATL-PHYS-PUB-2021-039 Nikhef

Extrapolation based on the full Run-2 result



Assumptions

- 3000 fb^{-1} ⇒ ~22×more data
- Cross-sections increase by 1.10-1.18 due to increase of CoM energy (13 → 14 TeV)
- **Most systematic uncertainties will reduce by 50%; uncertainties due to limited simulated sample sizes will be negligible (!)**

Results

Exp. signal strength: $\mu_{V(H\rightarrow cc)} = 1 \pm 2.0$ (stat.) ± 2.6 (syst.)

Exp. constraint @95% CL: $|\kappa_c| < 3.0$

- Results are systematically limited; by far dominant uncertainty: Z+jets modelling
  - Tested *different assumptions* regarding the systematic uncertainties: 5-10% changes on the limit each
- **Improved *b*-(light)-jet *c*-tagging rejections** by ×1.5 (3) thanks to the inner detector upgrade (Itk) ⇒ **+10-15%** improved limit (with the same DL1c tagger)

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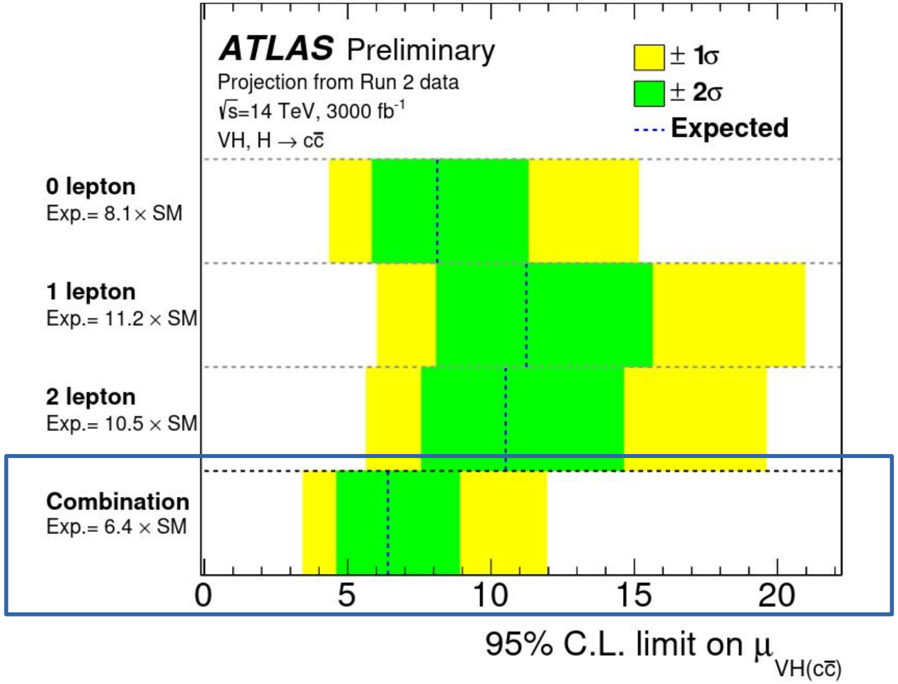

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Summary and conclusions

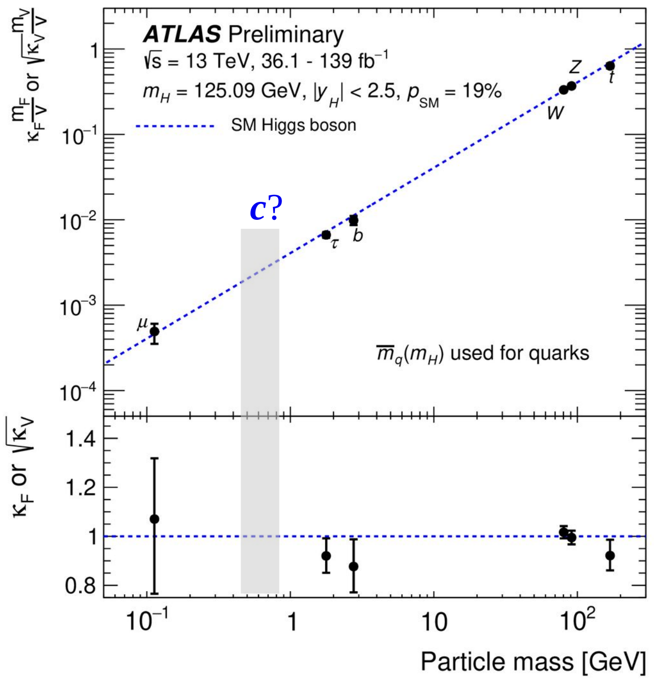
- Studying Higgs-charm coupling is among the most important open tasks in current Higgs physics

- Most promising approach to ***directly*** **probe the charm-Yukawa coupling** at the LHC: $\boldsymbol{VH(\rightarrow cc)}$

- ATLAS' full Run-2 $VH(\rightarrow cc)$ search provides
  - **Most stringent limit on $\boldsymbol{H\rightarrow cc}$ to date**
  - **First direct constraint on charm-Yukawa coupling**
  - 'Measurement' of VW/VZ with *c*-tagging

- Measurements of p_T(H) spectra in $H\rightarrow 4l$ (and $H\rightarrow \gamma\gamma$) provide **comparable *indirect* constraints on $\boldsymbol{\kappa_c}$**

- HL-LHC extrapolation results promising
  - Significant work to reduce (modelling) uncertainties necessary



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