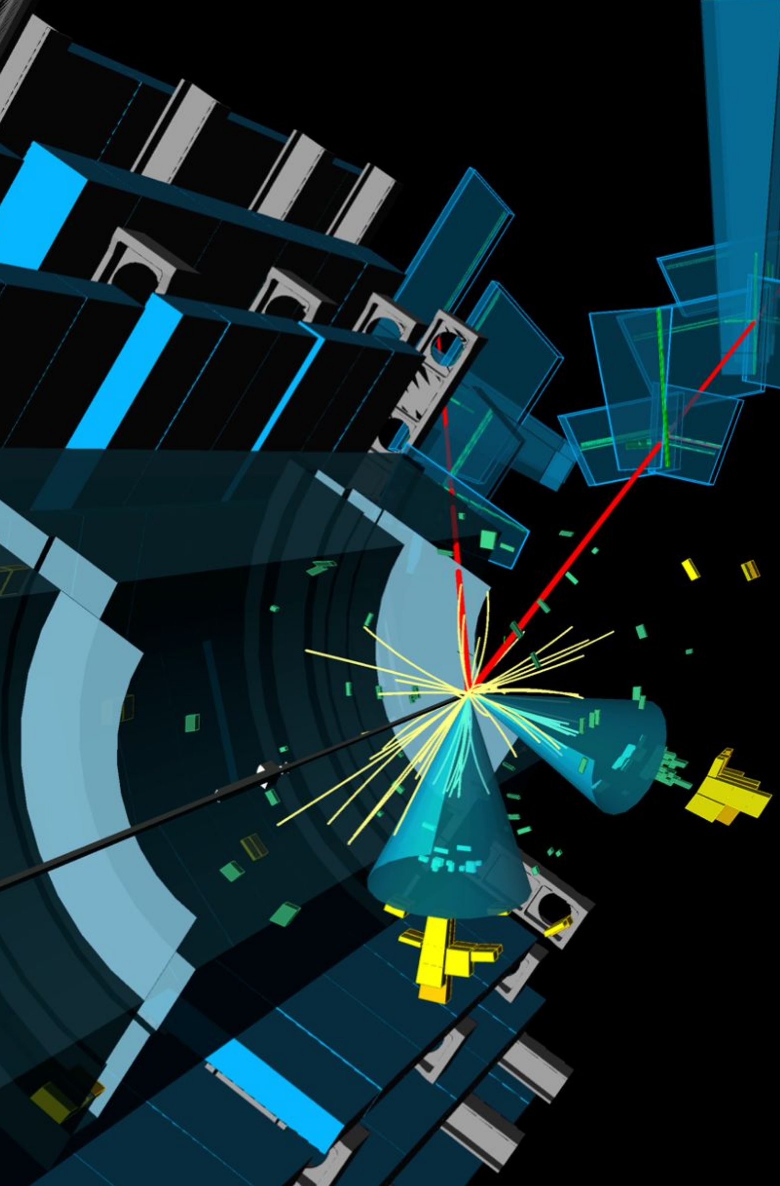


Search for the Higgs boson decay to charm quarks at the ATLAS experiment

Hannah Arnold (Nikhef)

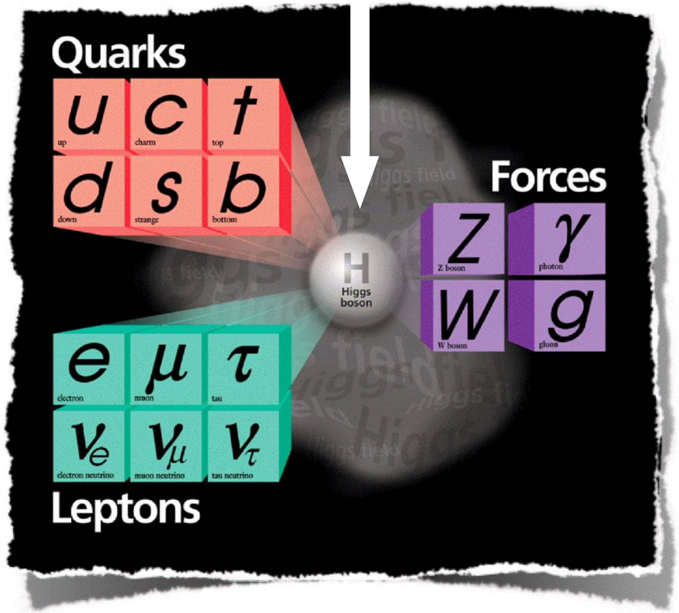
DPhP Seminar, CEA-Saclay
November 15, 2021

The Higgs boson discovered – end of (a long) story?

Nikhef

At the centre of the *Standard Model*

Courtesy Fermilab Visual Media Services



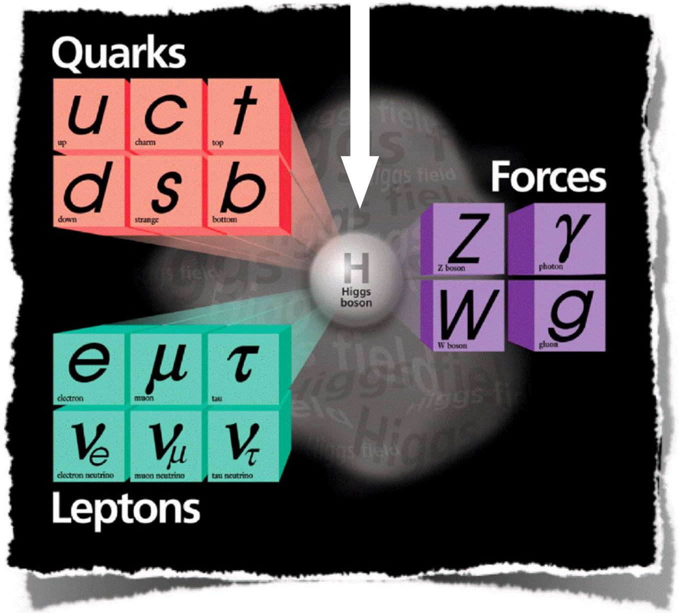
All known elementary particles

Discovered in 2012 as the last missing piece – 50 years after its prediction

The Higgs boson discovered – ~~end of (a long) story?~~

just the beginning

At the centre of the *Standard Model*



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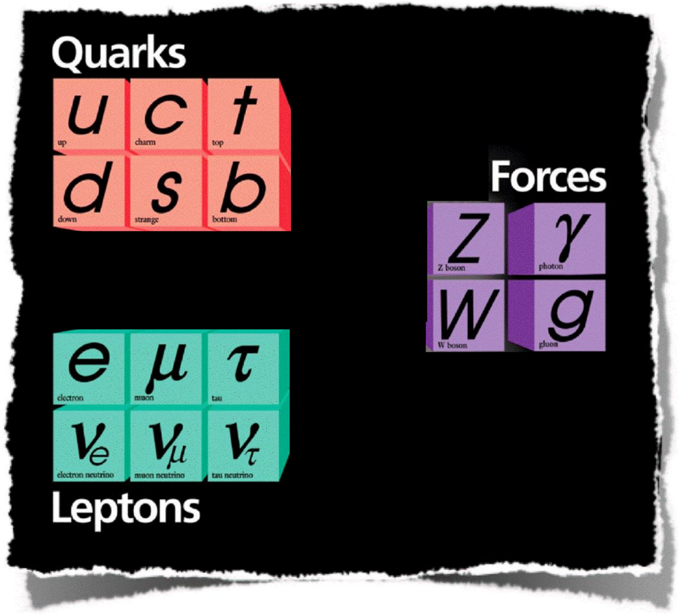
The Standard Model *without* the Higgs boson



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… describes the dynamics and interactions of **massless** *fermionic* particles (**quarks** and **leptons**) by exchange of **massless** *bosonic* mediators (**gauge bosons**)

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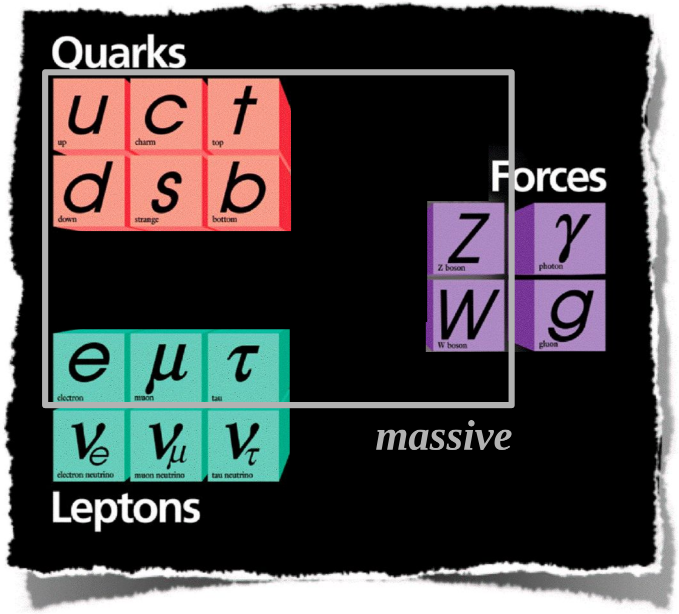

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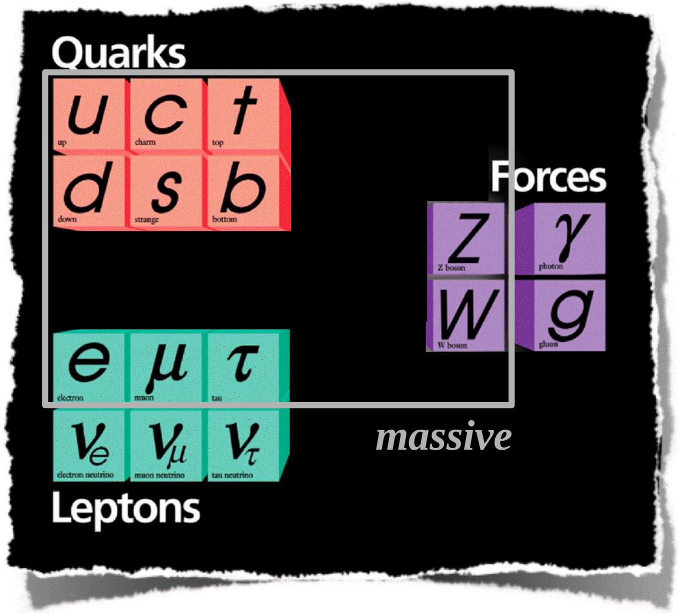
the ***W* and *Z* bosons** and the **charged fermions** are ***massive!***

The Standard Model *without* the Higgs boson



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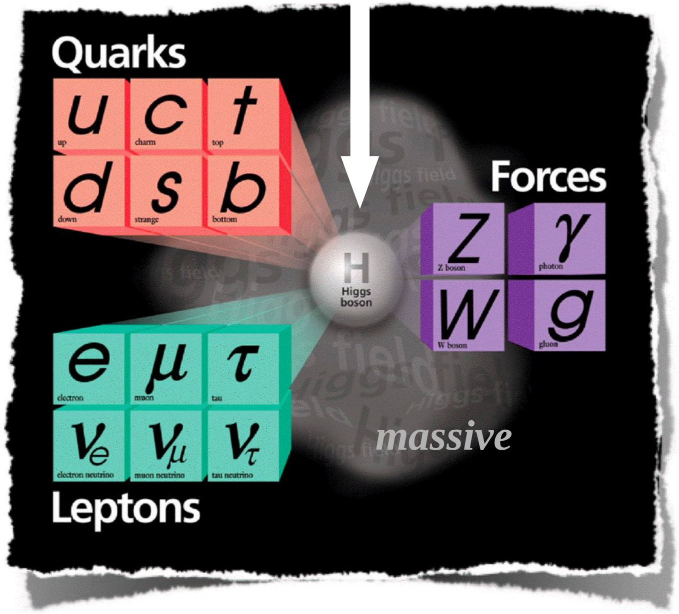
Solutions:

+ **Brout-Englert-Higgs mechanism**
+ **Yukawa couplings**

The Standard Model ~~without~~ the Higgs boson

Nikhef

At the centre of the *Standard Model*



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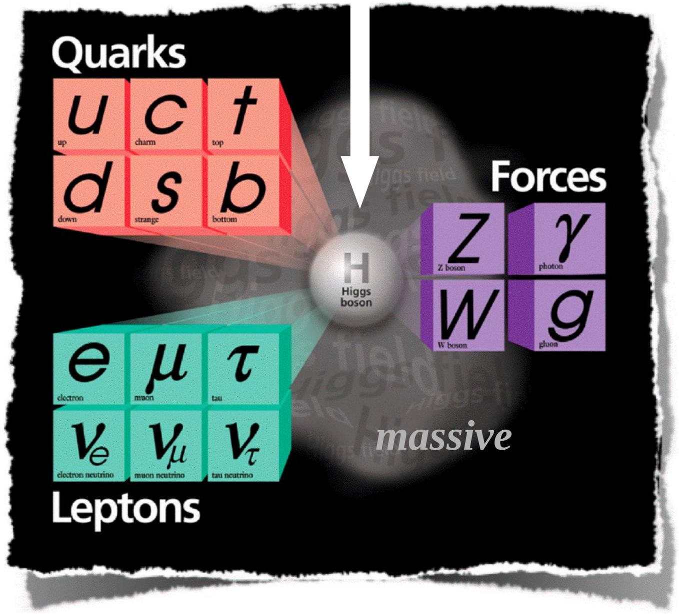
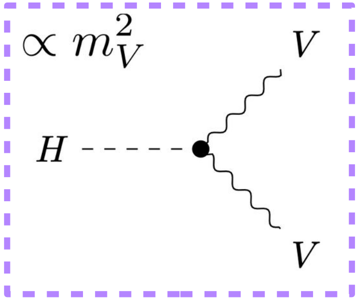
The Higgs boson couplings

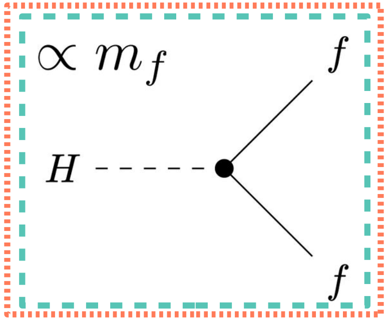
At the centre of the *Standard Model*



All known elementary particles



***W* and *Z* bosons**

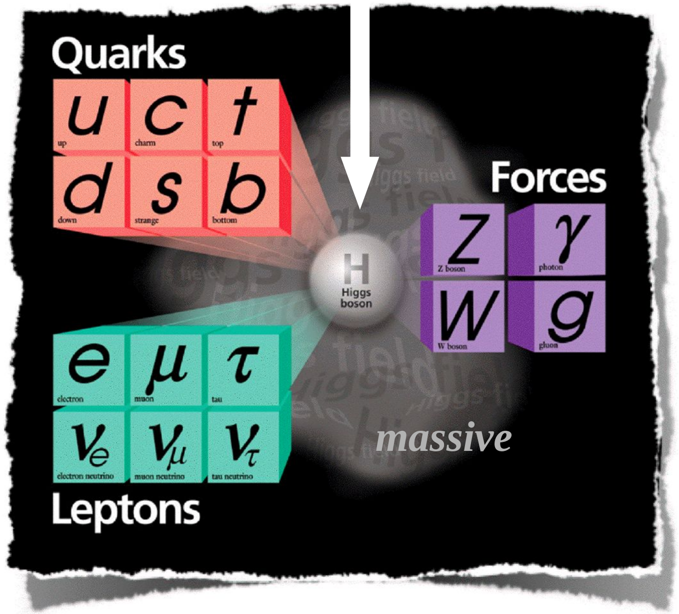


leptons
quarks

+ self-interaction...

The Higgs boson couplings

At the centre of the *Standard Model*



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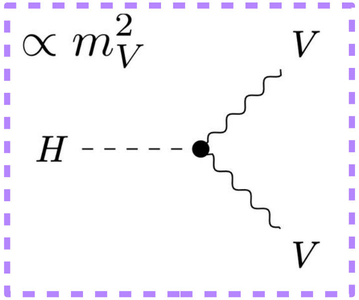
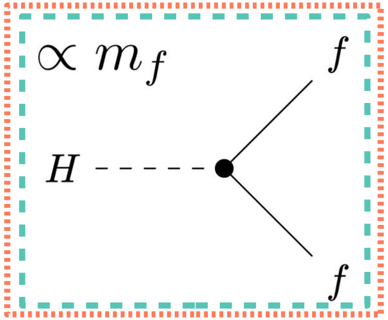


W and *Z* bosons

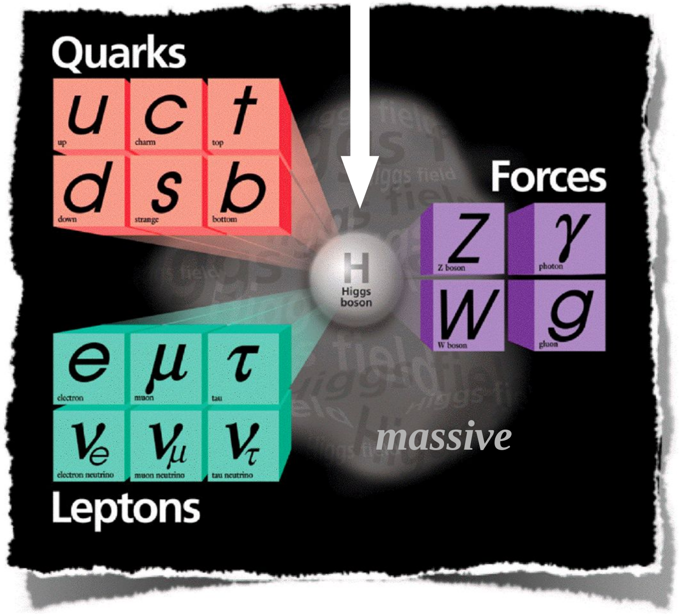


leptons
quarks

⇒ test by studying the observed Higgs boson’s production and decay

The Higgs boson couplings

At the centre of the *Standard Model*



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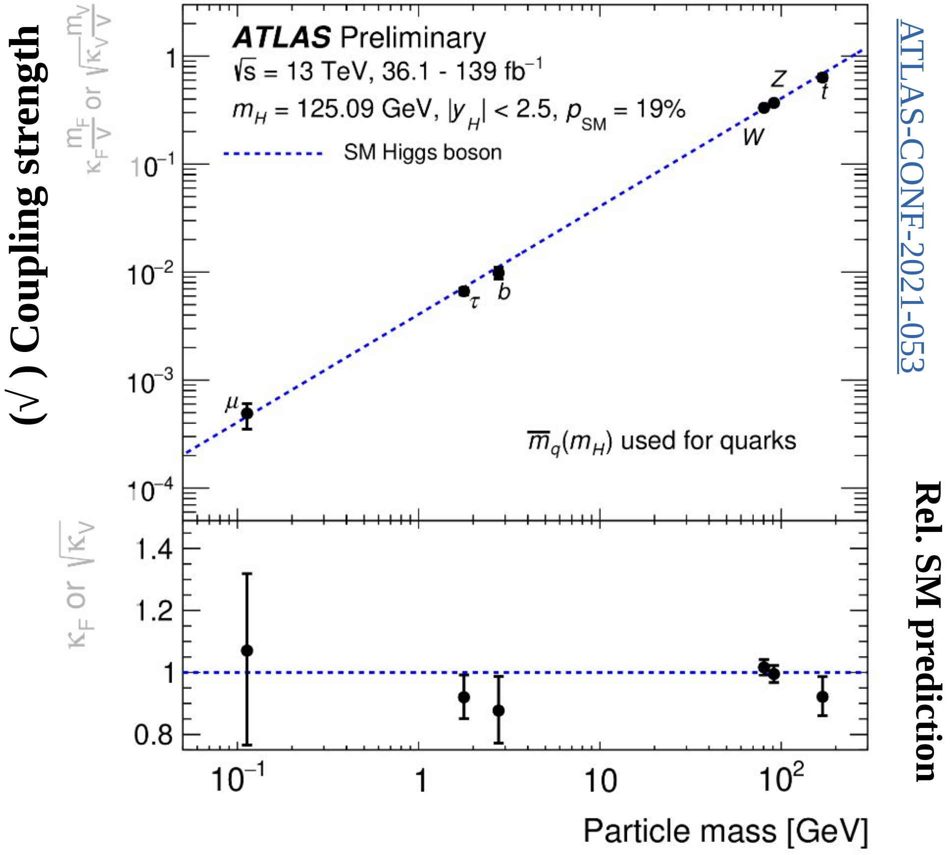
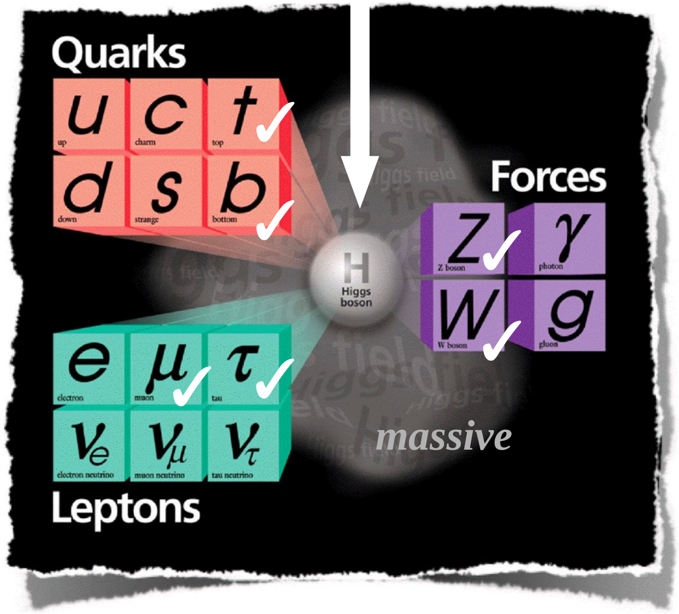


ATLAS-CONF-2021-053

So far excellent agreement with the prediction!

The Higgs boson couplings

At the centre of the *Standard Model*



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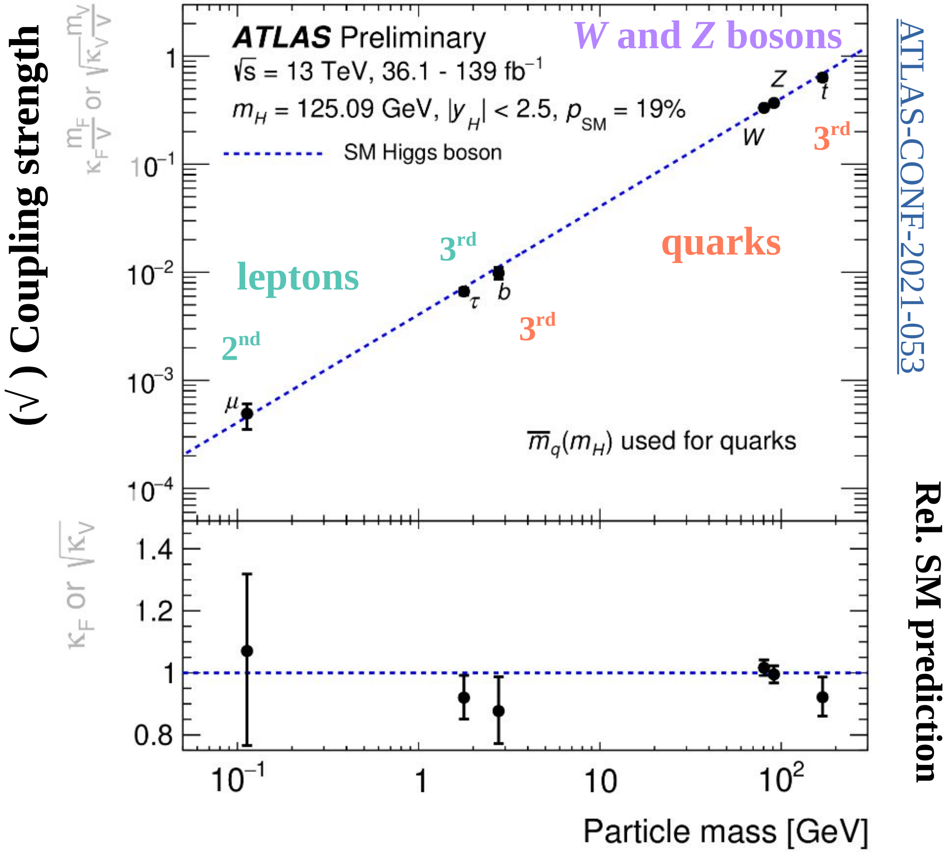

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The Higgs boson couplings

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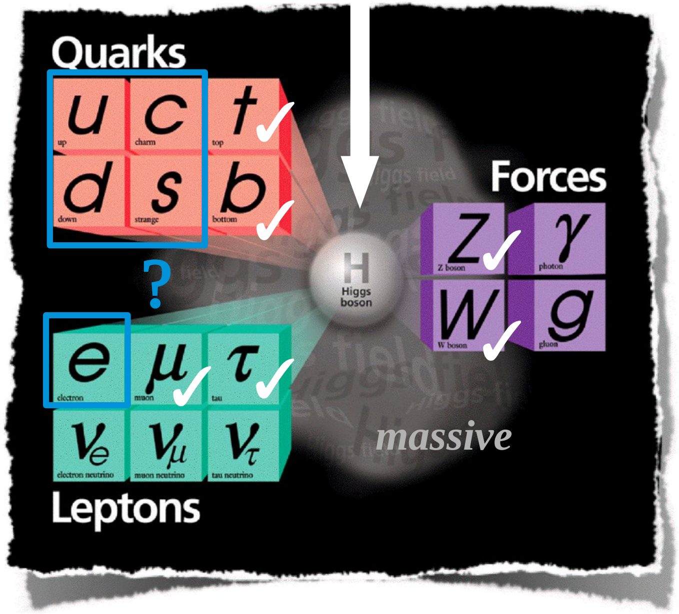

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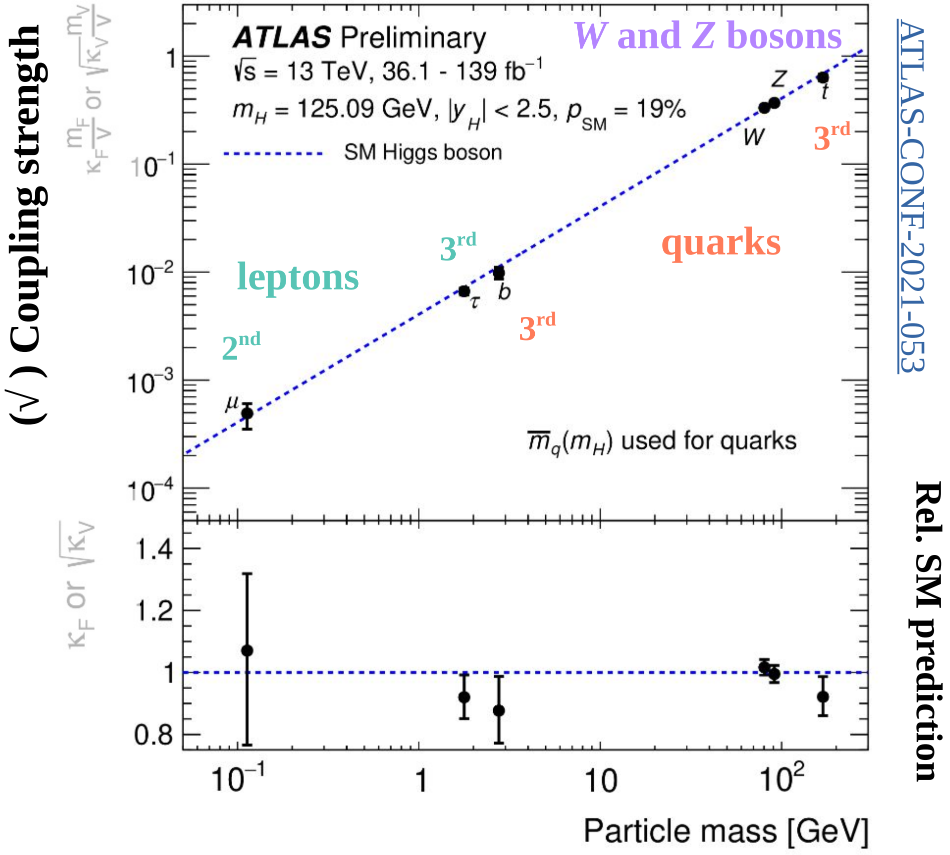
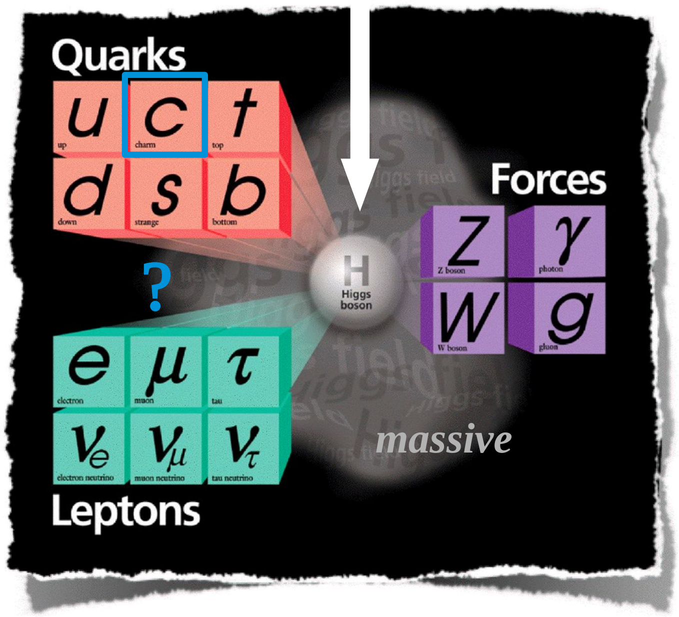


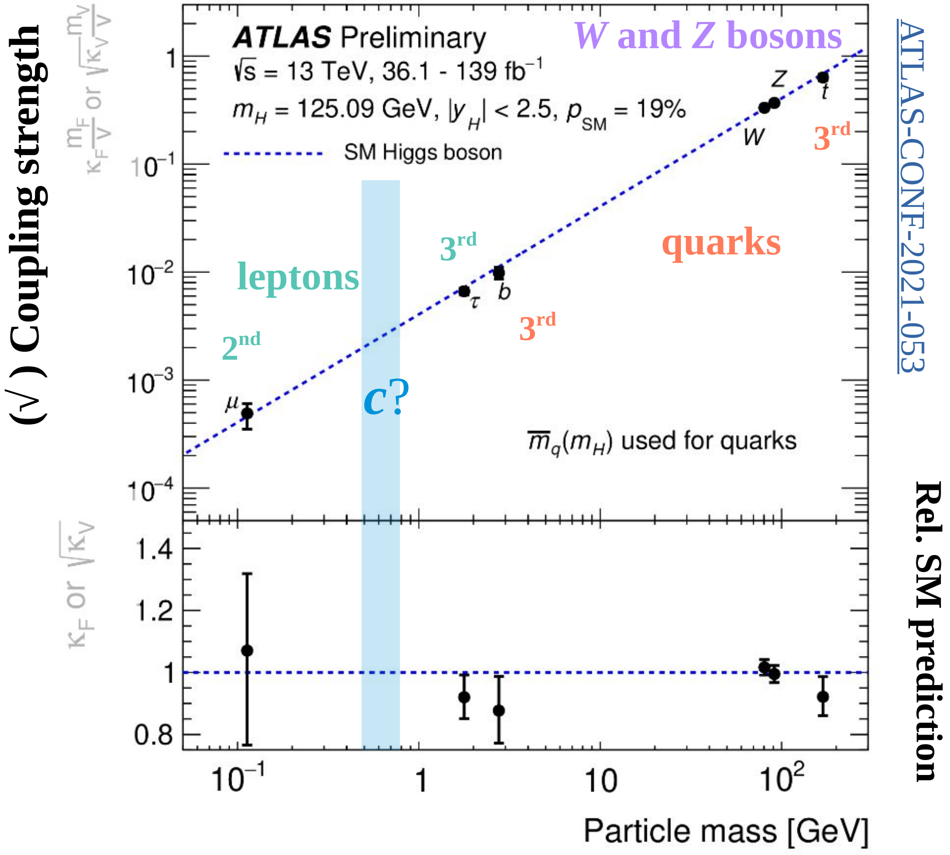
Couplings to electrons and 1st and 2nd generation quarks?

The Higgs boson couplings

At the centre of the *Standard Model*



All known elementary particles



Coupling to charm quarks?

The Higgs boson coupling to charm quarks

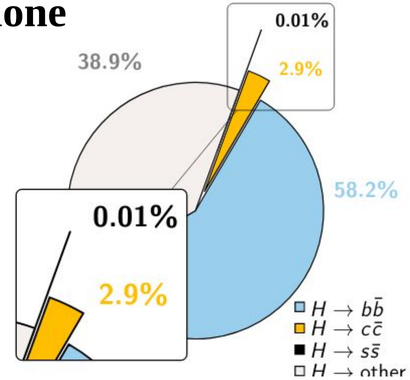
Why is it important to measure it?

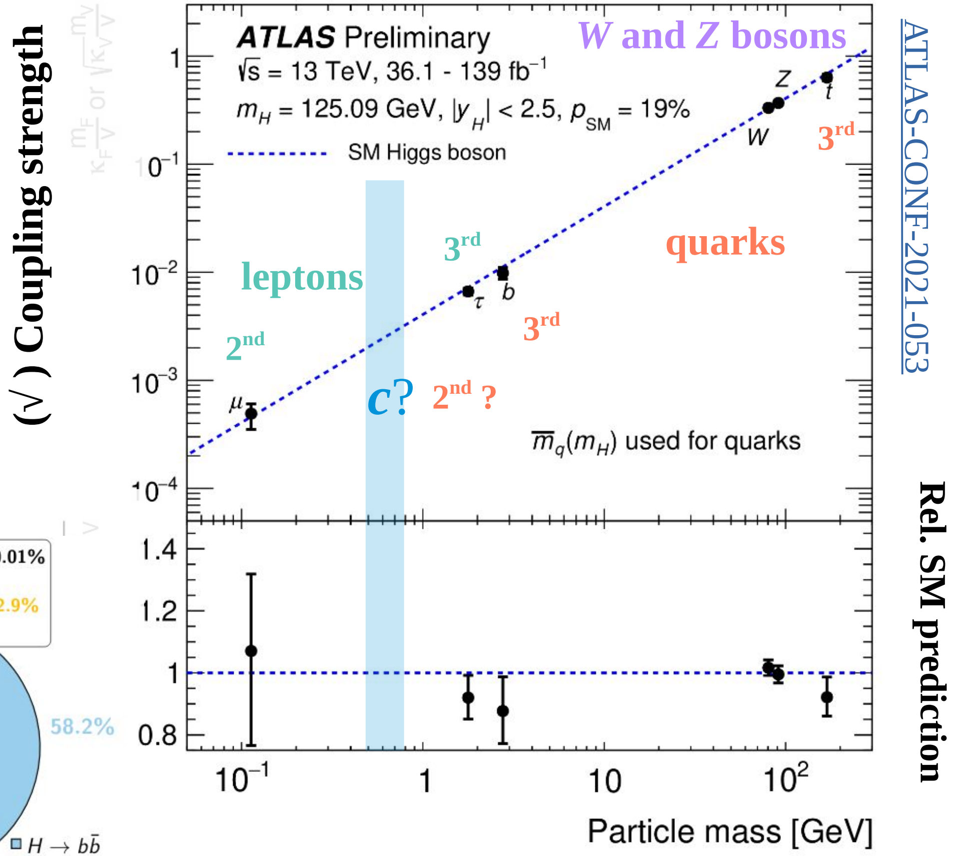
Probe of Higgs couplings to 2nd generation quarks – the only viable?

Its smallness in the SM makes it **susceptible** to possible **modifications from potential beyond-the-SM (BSM) models**

Many BSM models **predict modifications of the Higgs couplings to 2nd (and 1st) generation fermions/quarks alone**

H*→ *cc largest contribution to the Higgs-boson width that we have **no evidence for yet**





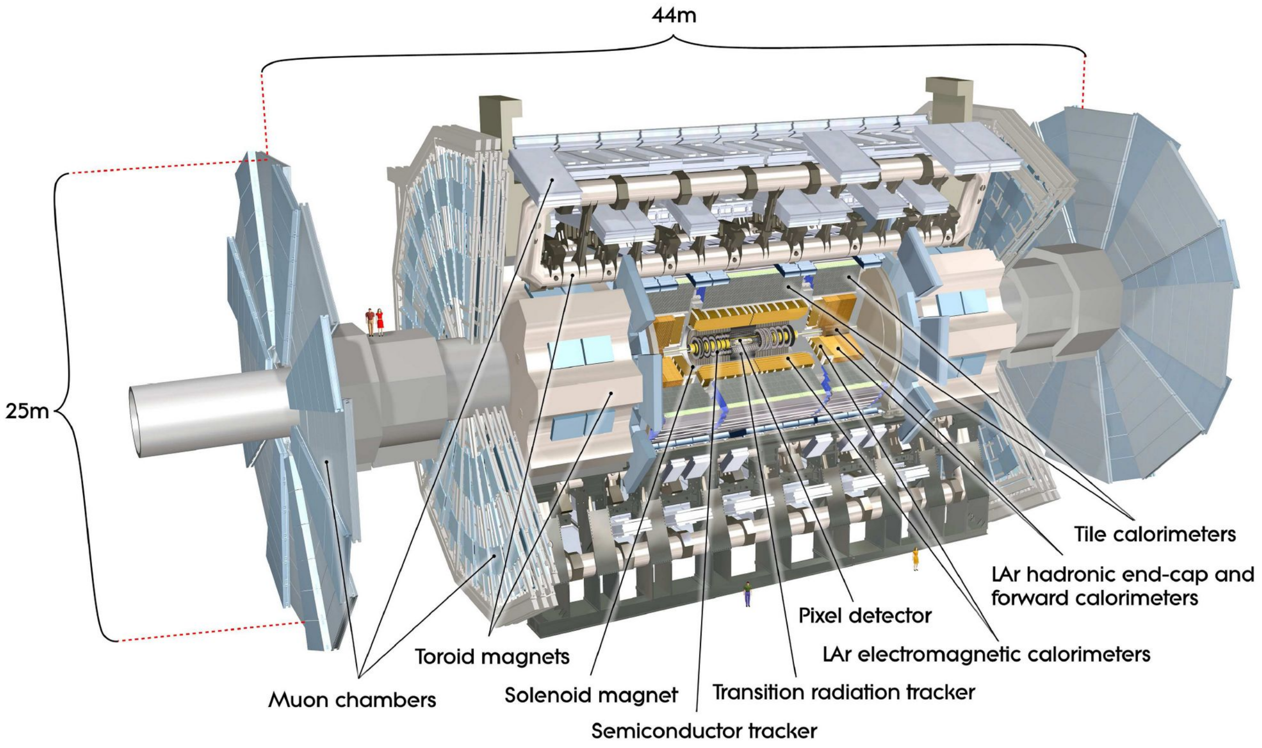
From A. Chisholm @Higgs Hunting 2021

Outline

- **Recent *VH, H→cc* search with the ATLAS detector based on the full Run-2 dataset** [ATLAS-CONF-2021-021]
  - Previous and first search [PRL 120 (2018) 211802]:
    - Based on 36 fb^{-1} of Run-2 data; targets $Z(\rightarrow ll)H(\rightarrow cc)$
    - Observed (expected) upper limit on σ×BR: 110 (150) × SM prediction
- HL-LHC projection for *VH, H→cc* search based on full Run-2 analysis [ATL-PHYS-PUB-2021-039]
  - Previous projection [ATL-PHYS-PUB-2018-016]: upper limit on σ×BR: 6.3 × SM prediction (w/o systematic uncertainties)
- Complementary approaches to constrain the Higgs-boson coupling to charm quarks

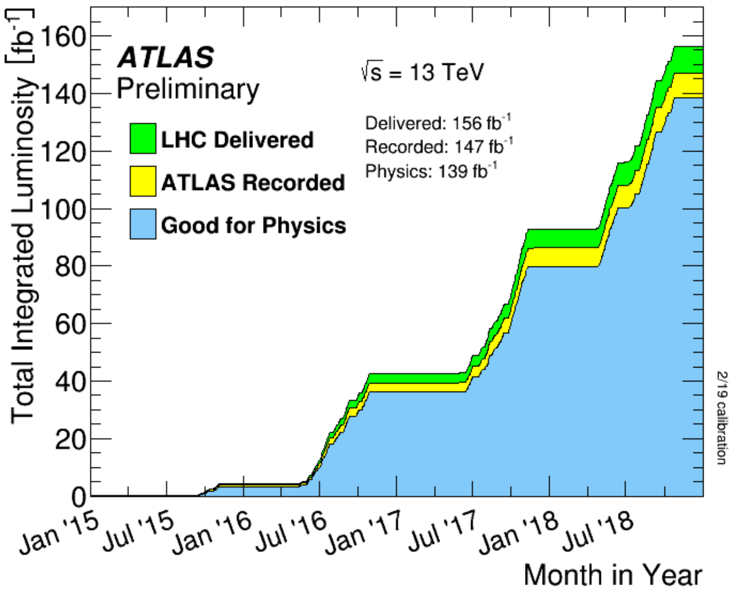
The data

Nikhef



Prerequisites:

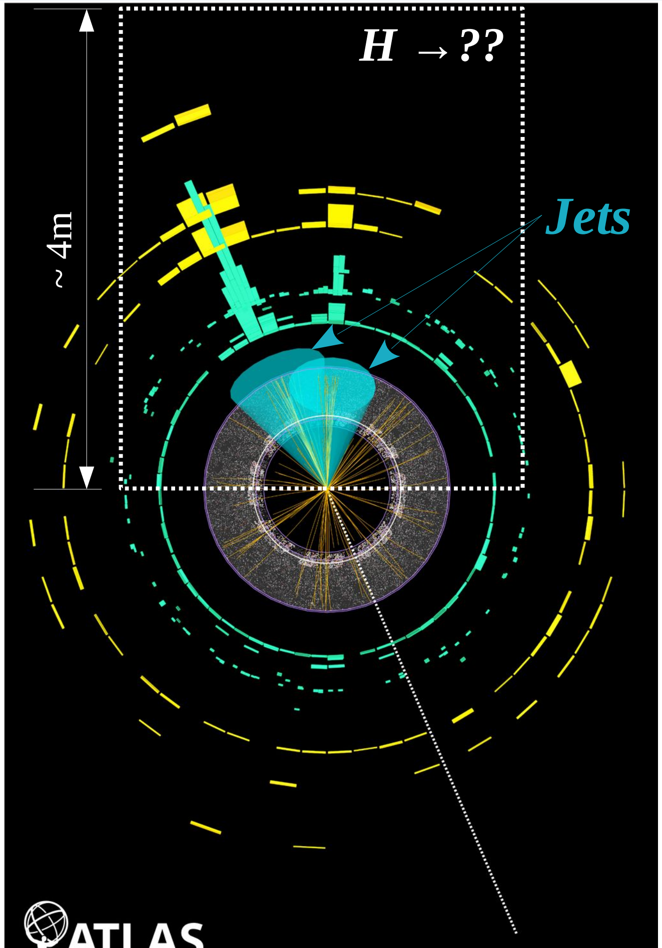
- Lots of high-quality *pp*-collision data provided by the LHC
- Excellent multi-purpose detector



ATLAS experiment

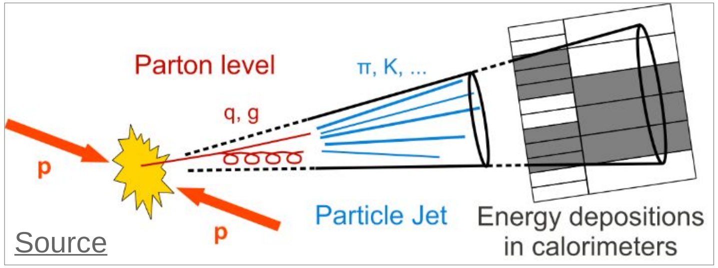
Challenge: how to identify $H \rightarrow cc$?

Nikhef

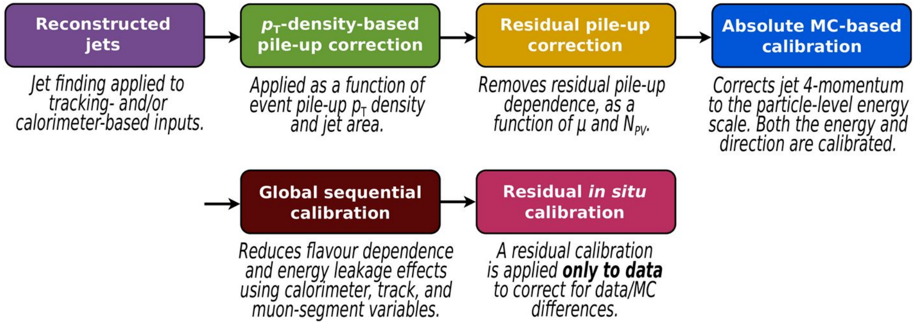


Adapted from source

1. Jet reconstruction

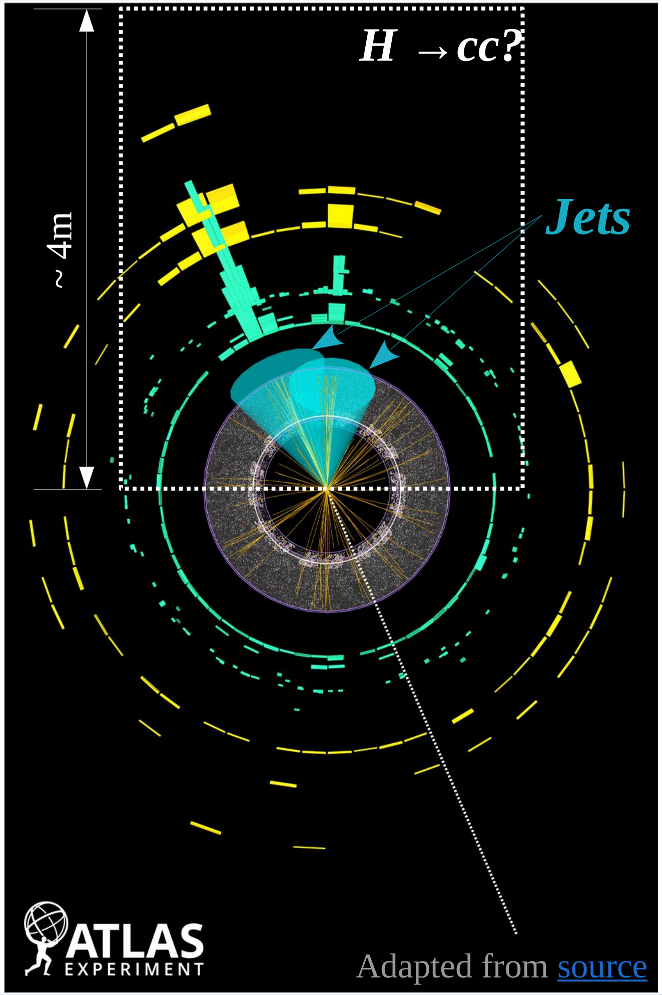


- Jet clustering algorithm: **anti-k_T** with radius-parameters R = 0.4
- Inputs: **Calorimeter energy clusters** (EMTopo)
- Calibration of the energy scale:



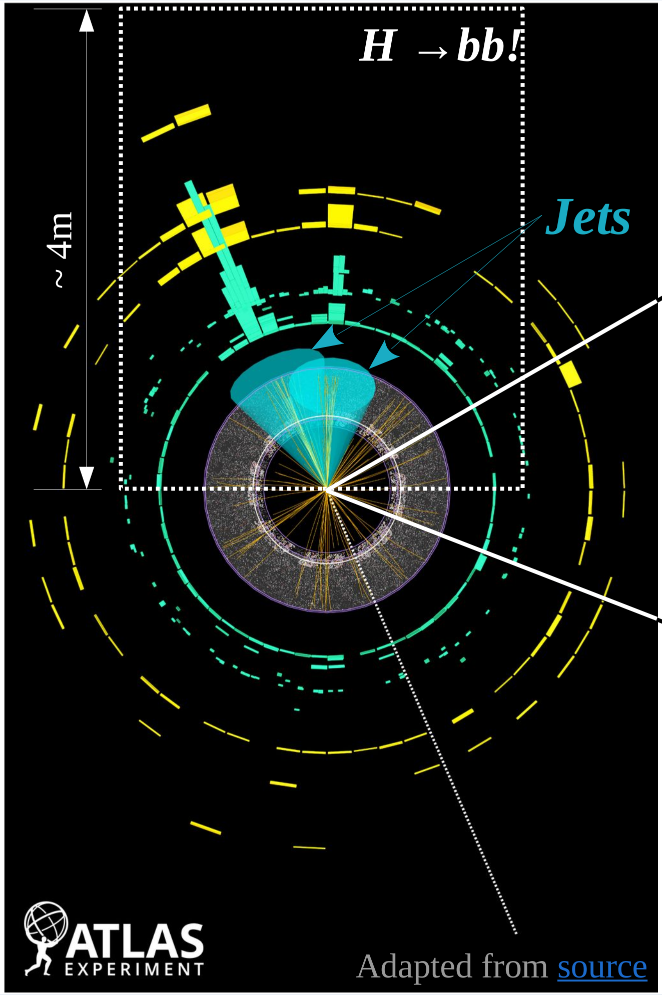
Eur. Phys. J. C 81 (2021) 689

Challenge: how to identify $H \rightarrow cc$?



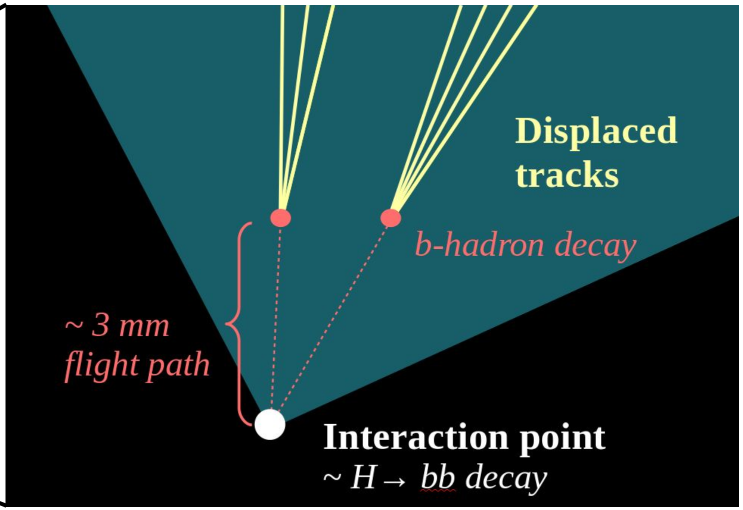
2. *c*-jet identification

Challenge: how to identify ~~$H \rightarrow cc$~~ $H \rightarrow bb$?



2. ~~c-jet~~ *b*-jet identification

ZOOM



Identification of jets containing *b*-hadrons

- "b-tagging"

Challenge: how to identify $H \rightarrow cc$?

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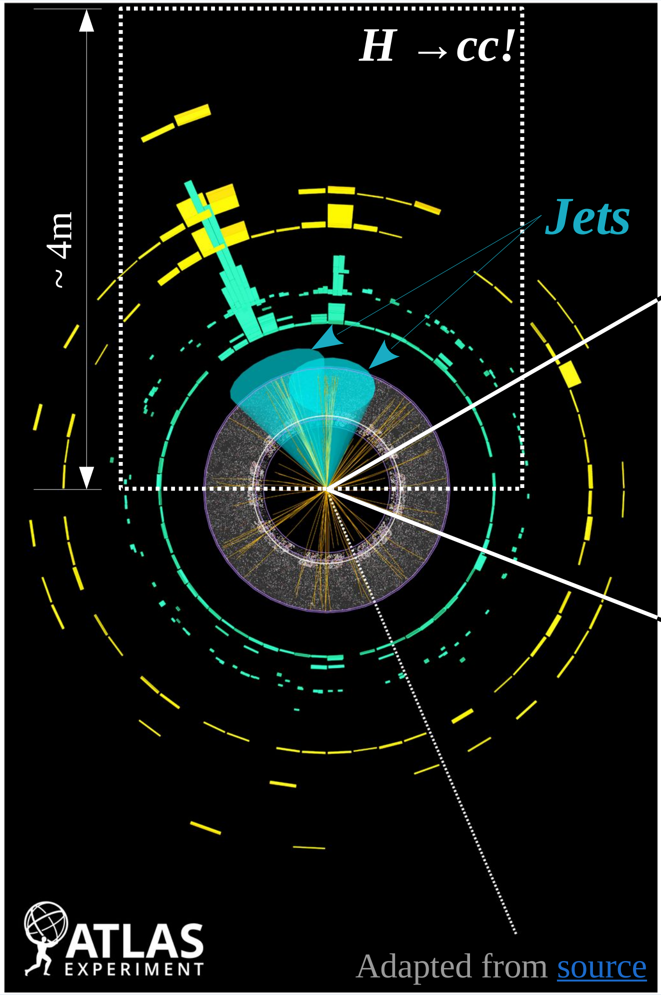
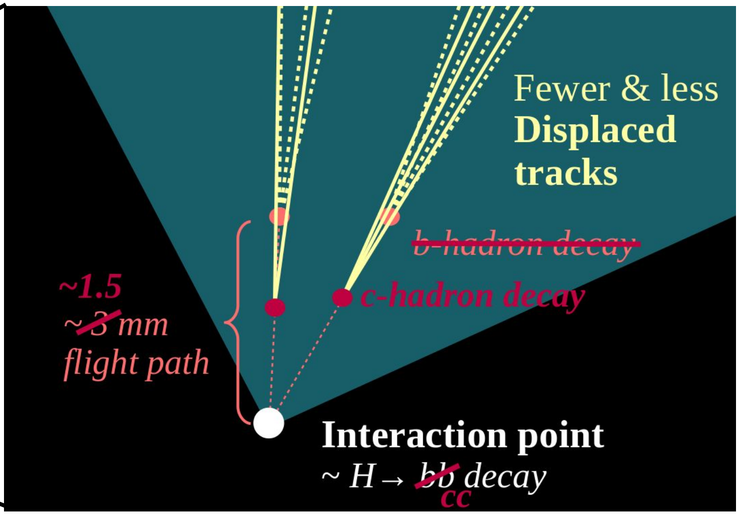


2. *c*-jet identification

ZOOM



More challenging – hardly explored yet

Identification of jets containing *c*-hadrons

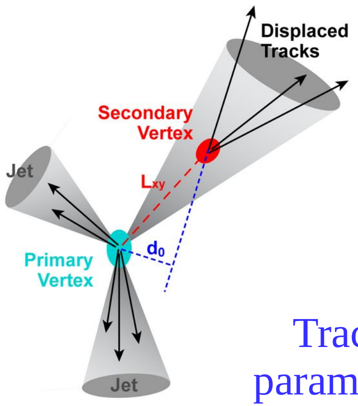
- “c-tagging”

c-tagging

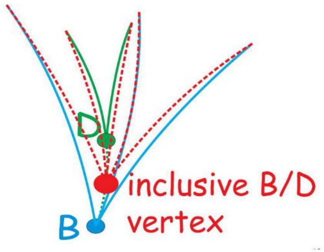
Current c-tagging strategy: use the algorithms developed for b-tagging, but train with c-jets as signal

Selection of "low-level" b-tagging algorithms

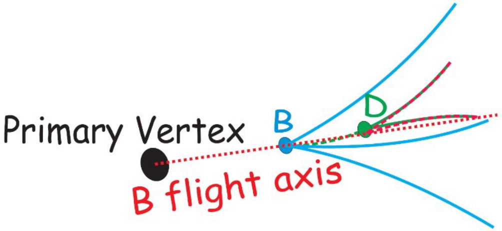
2008 J. Phys.: Conf. Ser. 119 032032



IP3D
Track impact-parameter based



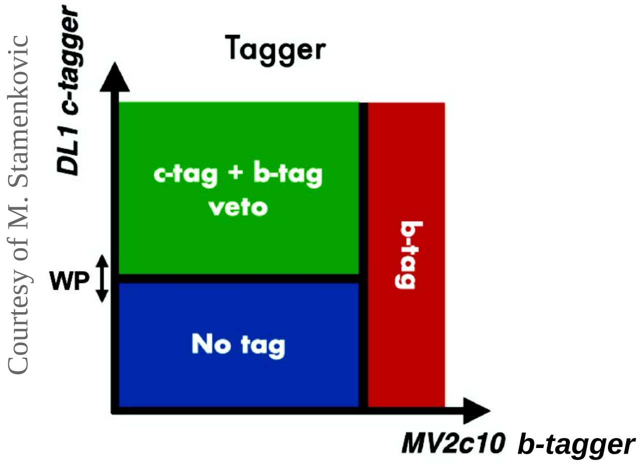
SV1
inclusive 2nd / 3rd vertex reconstruction



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

Multivariate analysis techniques used to combine low-level tagger output into final discriminants, e.g. **MV2c10** (BDT-based b-tagger), **DL1c** (DNN based c-tagger)

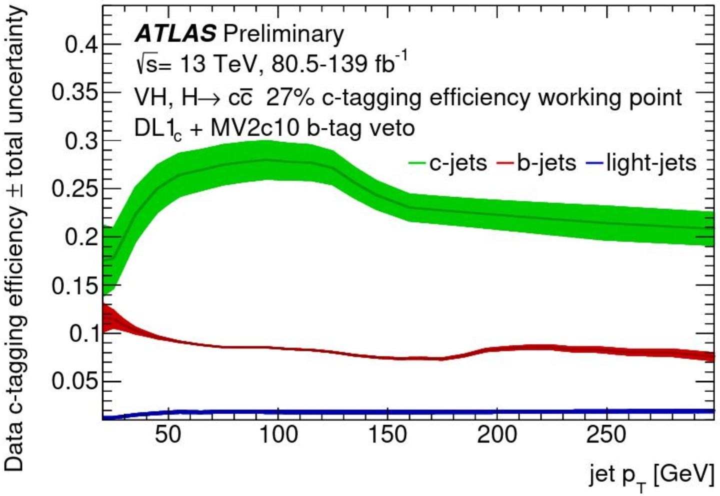
c-tagging: the $VH(\to cc)$ strategy



Dedicated c-tagging:

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

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



(Average) performance (on ttbar)

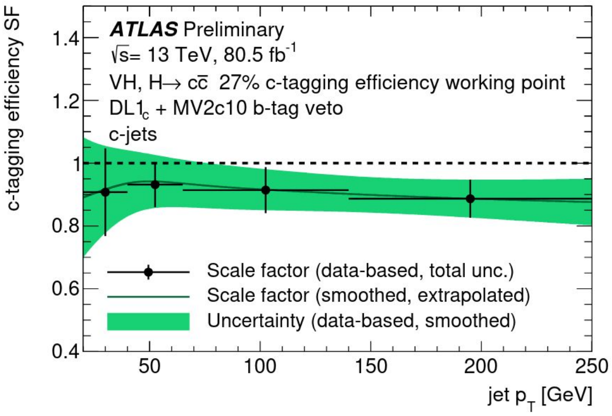
	c-tag eff
c-jets	27%
b-jets	8%
l-jets	1.6%

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

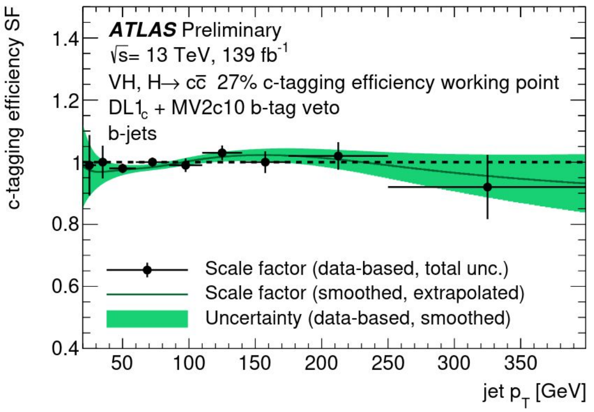
c-tagging: calibrations

Nikhef

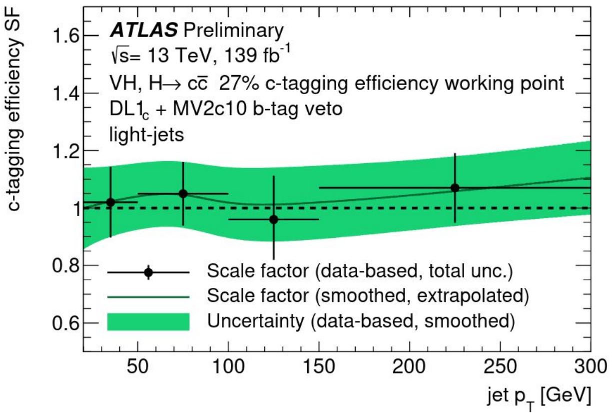
c-jets



b-jets



light jets



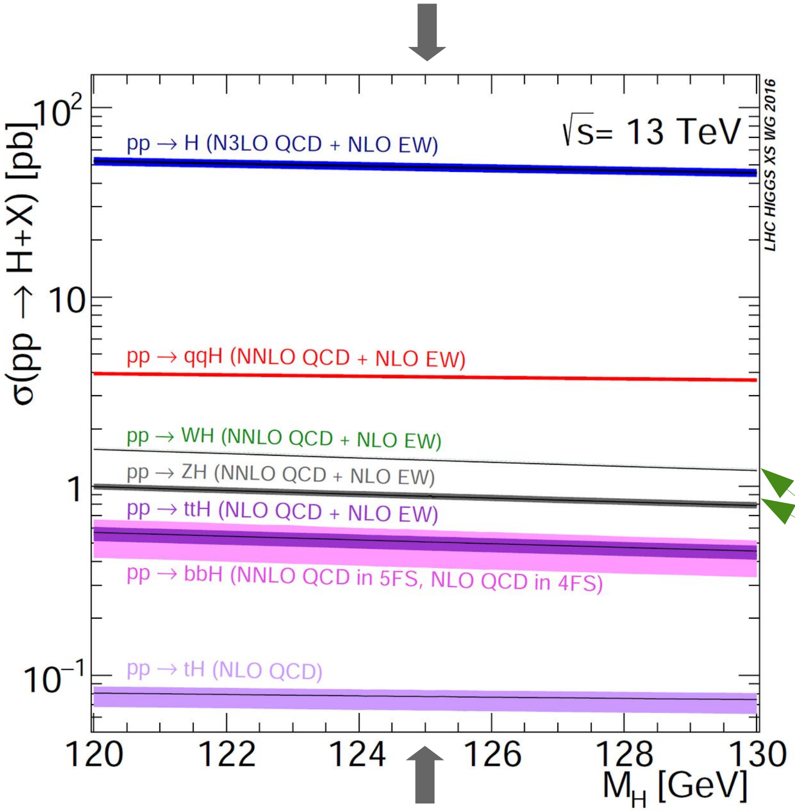
Dedicated calibrations for *c*-, *b*- and light-quark jets using “standard” b-tagging calibration methods(*)

⇒ jet p_T and η dependent data-to-simulation scale factors (per parton shower)

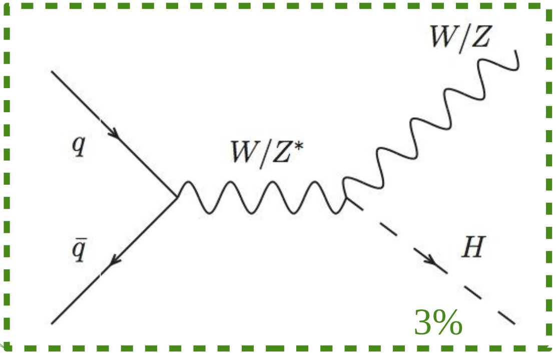
⇒ uncertainties: at most 15%

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

Why $VH, H \to cc$?



VH

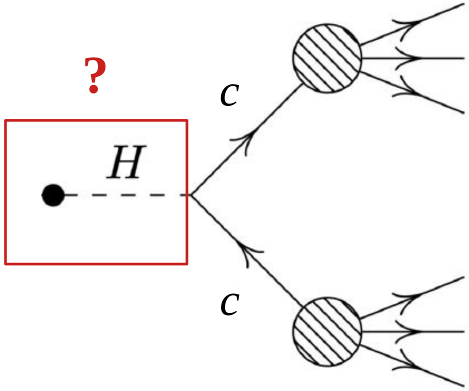


"the golden channel"

Challenge: $H \to cc$ at the LHC

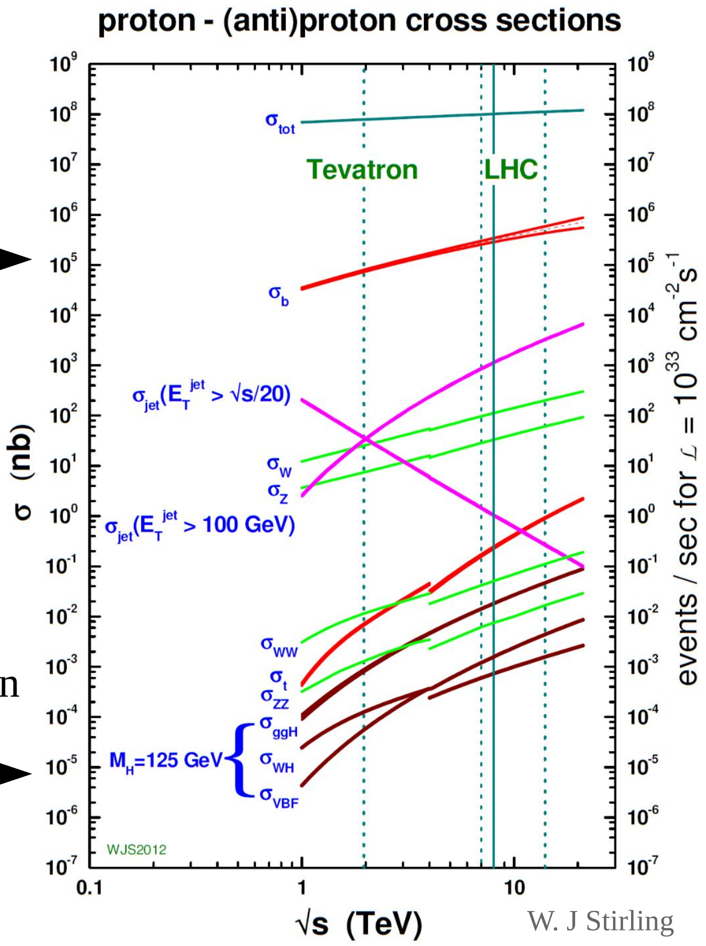
LHC: proton-proton collisions

<u>Challenge</u>: find a *pair of c-jets* in an overwhelming *multi-(c)-jet* background



quark/jet production

Higgs-boson production



W. J Stirling

LHC: proton-proton collisions

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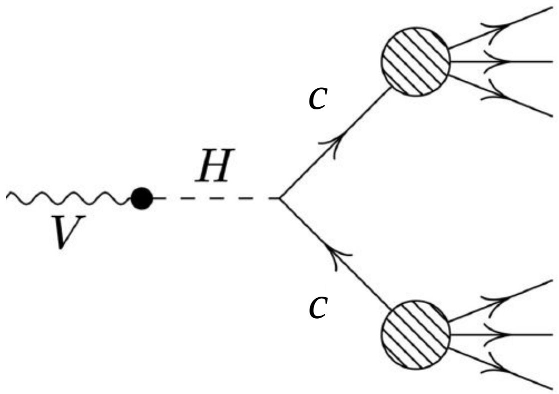
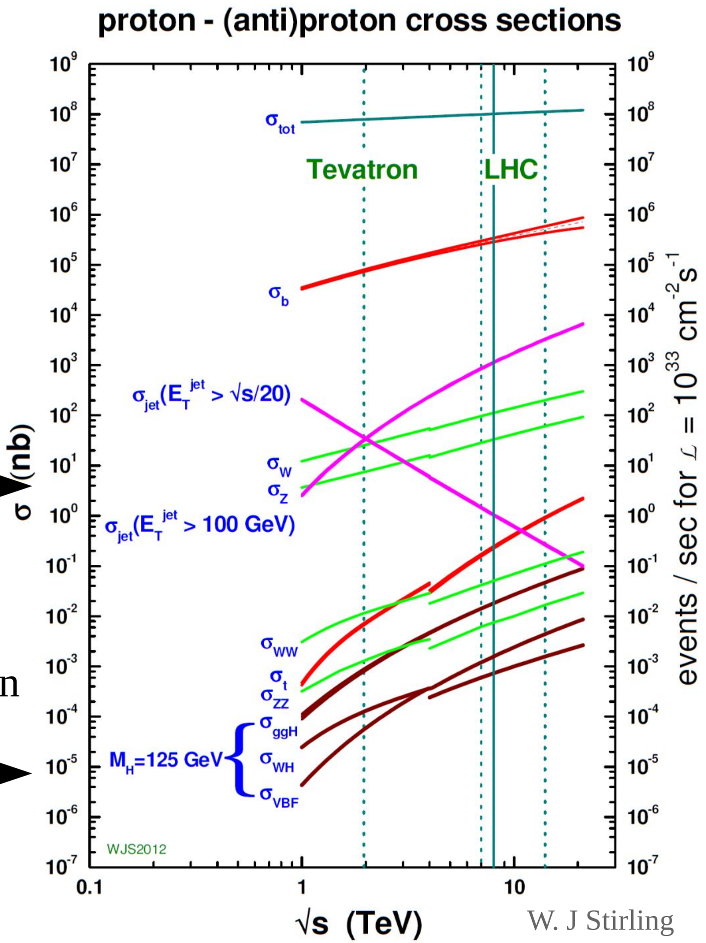


V+jet production

Higgs-boson production

Solution: ***VH* production**

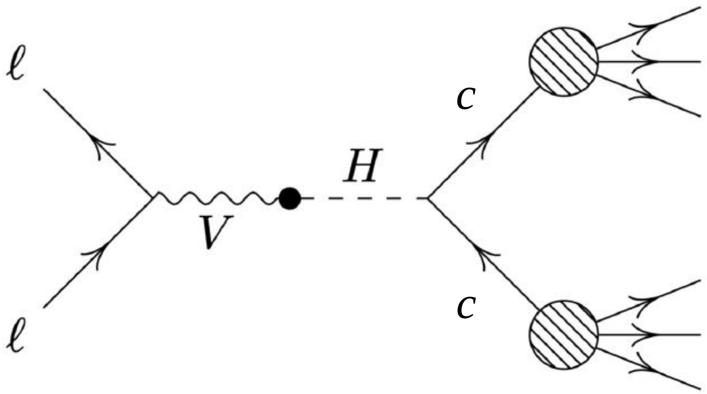


W. J Stirling

Challenge: $H \to cc$ at the LHC

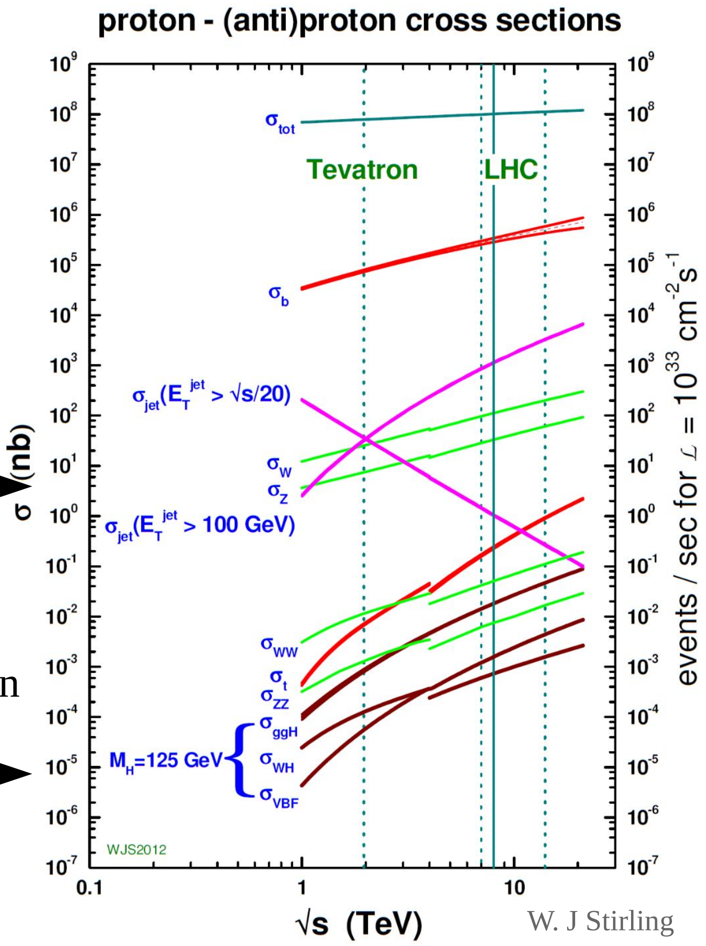
LHC: proton-proton collisions

Challenge: find a *pair of c-jets* in an overwhelming *multi-(c)-jet* background



V+jet production

Higgs-boson production

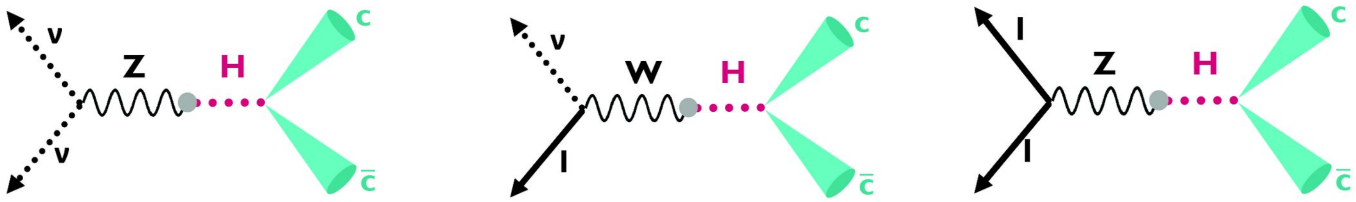


W. J Stirling

Solution: ***VH* production**
+ leptonic V-boson decays
⇒ background suppression + triggering

Putting things together: $VH(\rightarrow cc)$ analysis strategy I

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

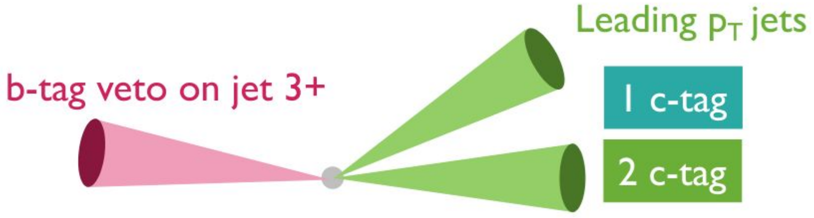


Courtesy of M. Mironova

⇒ triggering: eletrons, muons or large missing transverse momentum (Etmiss)

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

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



1 and 2 c-tag categories

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

⇒ Orthogonality to VH(→bb)

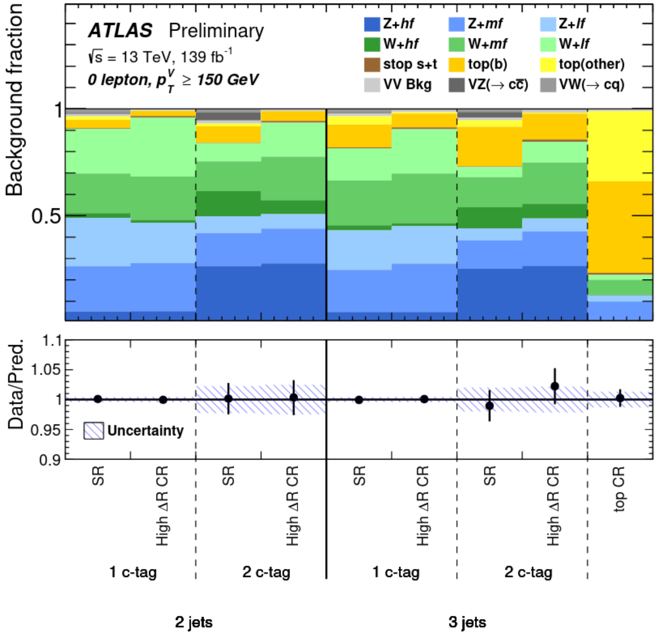
Categorisation in p_T(V) and # of jets ⇒ isolate regions with better S/(√)B

Putting things together: $VH(\rightarrow cc)$ analysis strategy II

Background estimate

- From *simulation*
  exception: multijet contribution in 1L (negligible in 0/2L (after selection))
- *Truth-flavour tagging* to maximise the statistical power of the samples
  weight events with the probability of each jet to be c-tagged(+b-tag veto)
- **Systematic uncertainties** from comparisons to alternative samples or simulation settings (acceptances, shapes)
- **Various control regions in data** ⇒ determine normalisation and constrain modelling uncertainties

0-lepton channel



Profile likelihood fit to extract *three* signal strengths simultaneously:

- **VH(→cc)**
- **VW(→cl), VZ(→cc)** ⬅ **coss-check signals** ⇒ validate analysis strategy

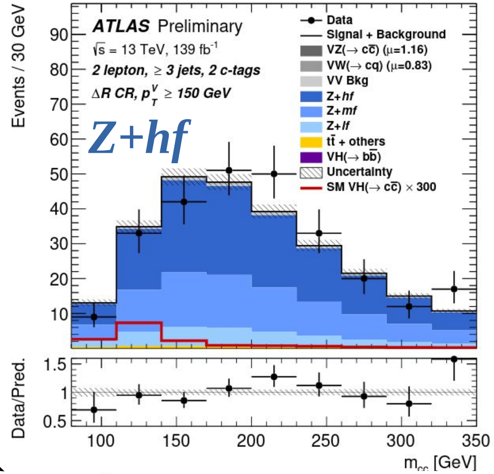
Large and diverse background contributions: Z+jets, W+jets, top

Control regions

Nikhef

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

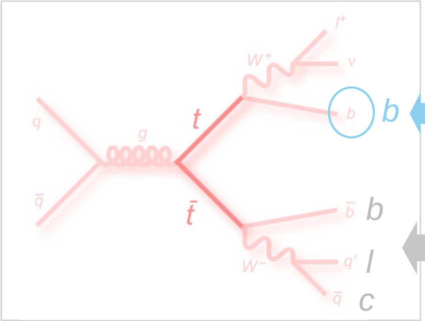
- V+hf = V+cc/bb ⇒ **2 c-tag high-ΔR CR**
- V+l ⇒ **0 c-tag "SR" – norm-only (1/2L)**
- V+mf = rest ⇒ **1 c-tag high-ΔR CR**



Top background (0/1L) (*)

- *top(b)*: Higgs-candidate jets *bx;* dominated by bc
- *top(other):* rest; dominated by *cl* (from W)

⇒ **top CR**: *inverted* b-tag veto on 3rd jet



b

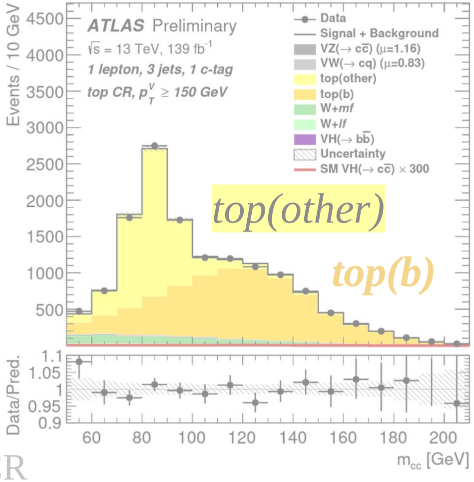
Suppressed in SR, enriched in CR

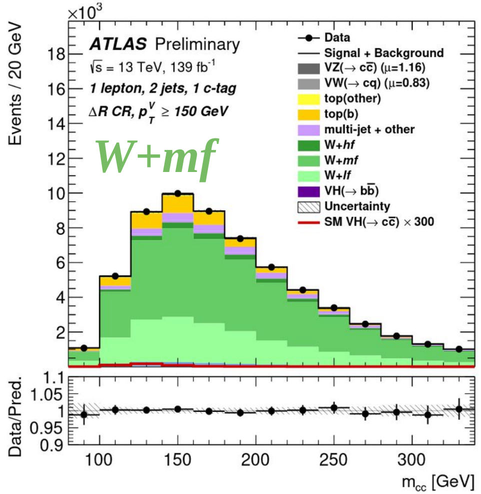
b

l

c

Higgs candidate





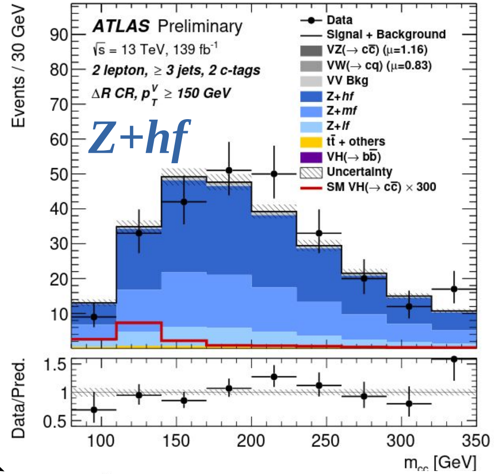
(*) In 2L (very) small contribution ⇒ norm-only *eμ* ttbar CR

Control regions

Nikhef

V+jets background (V = W, Z)

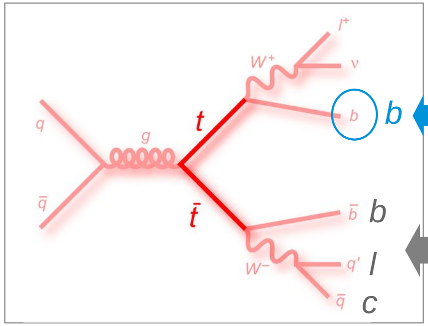
- V+hf = V+cc/bb ⇒ **2 c-tag high-ΔR CR**
- V+l ⇒ **0 c-tag "SR" – norm-only (1/2L)**
- V+mf = rest ⇒ **1 c-tag high-ΔR CR**



Top background (0/1L) (*)

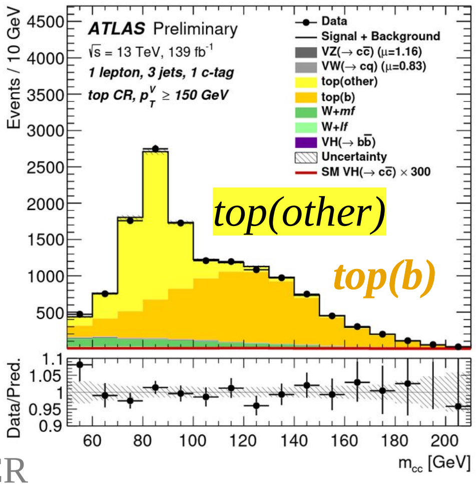
- *top(b)*: Higgs-candidate jets *bx;* dominated by *bc*
- *top(other):* rest; dominated by *cl* (from W)

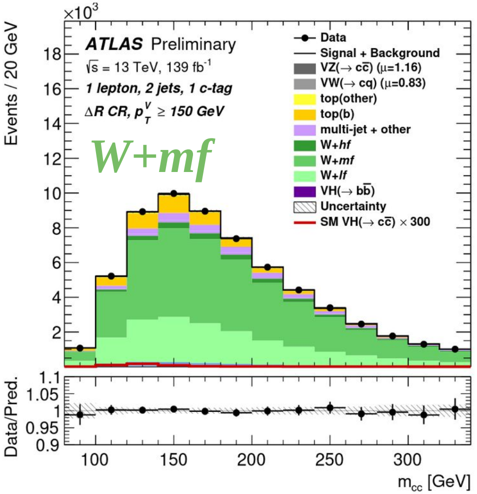
⇒ **top CR**: *inverted* b-tag veto on 3rd jet



Suppressed in SR, enriched in CR

Higgs candidate





(*) In 2L (very) small contribution ⇒ norm-only *eμ* ttbar CR

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		

Summary analysis regions

Nikhef

Courtesy of M. Mironova

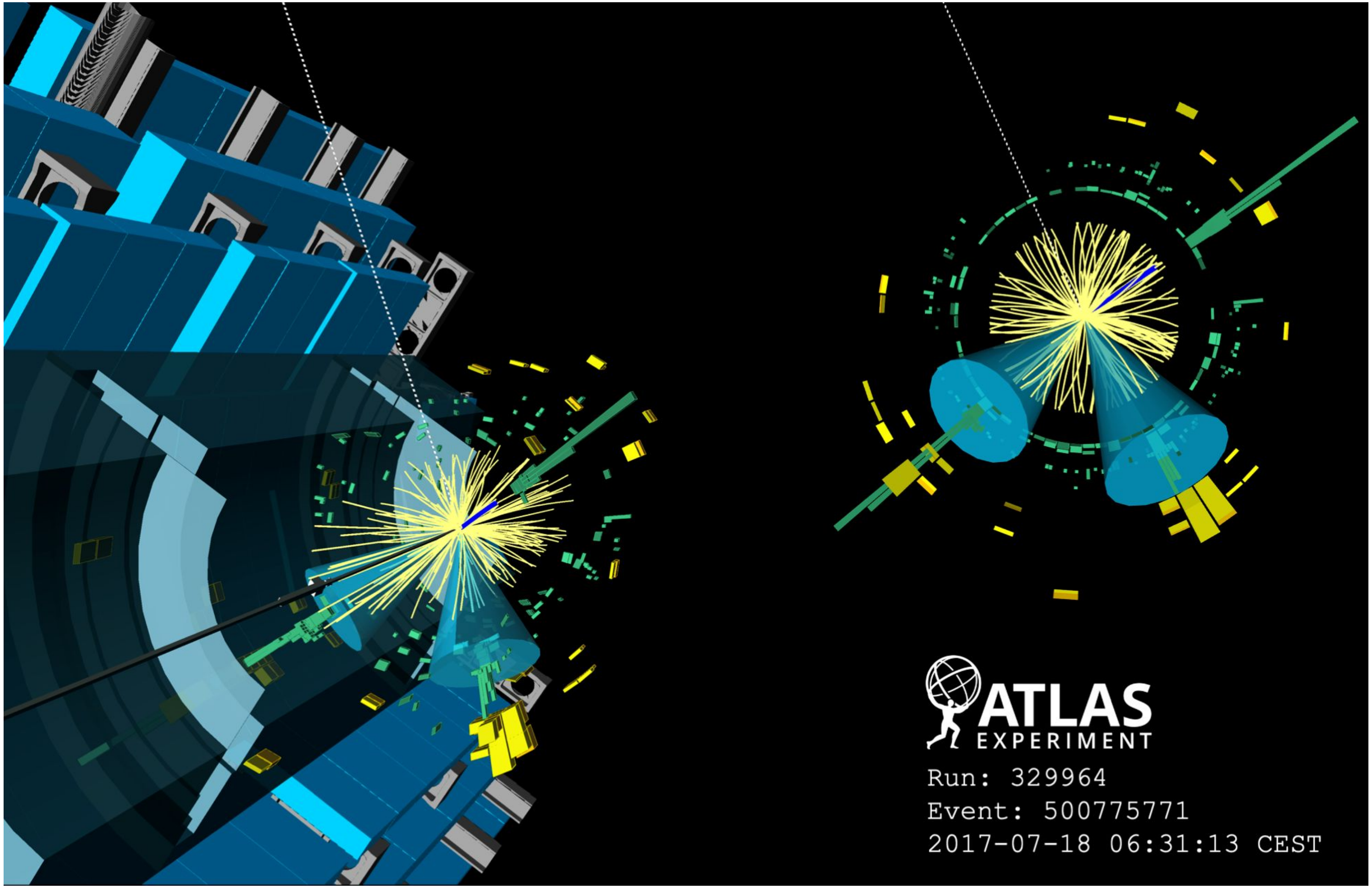
16 Signal Regions

28 Control Regions

		0 c-tag CR		SR		Top CR		ΔRcc CR	
		ΔRcc < ΔRcc selection						ΔRcc selection < ΔRcc < 2.5	
0L	pTV > 150 GeV		10	1 c-tag 2 jet	2 c-tag 2 jet	1		1 c-tag 2 jet	2 c-tag 2 jet
			7	1 c-tag 3 jet	2 c-tag 3 jet	0.7	jet	1 c-tag 3 jet	2 c-tag 3 jet
1L	pTV > 150 GeV	0 c-tag	7	1 c-tag 2 jet	2 c-tag 2 jet	0.9		1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag	5	1 c-tag 3 jet	2 c-tag 3 jet	0.6	jet	1 c-tag 3 jet	2 c-tag 3 jet
2L	75 < pTV < 150 GeV	0 c-tag	3	1 c-tag 2 jet	2 c-tag 2 jet	0.3	2 jet	1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag	3	1 c-tag 3+ jet	2 c-tag 3+ jet	0.3	+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet
	pTV > 150 GeV	0 c-ta	1.5	1 c-tag 2 jet	2 c-tag 2 jet	0.2	2 jet	1 c-tag 2 jet	2 c-tag 2 jet
		0 c-tag	2	1 c-tag 3+ jet	2 c-tag 3+ jet	0.2	+ jet	1 c-tag 3+ jet	2 c-tag 3+ jet
		Norm-only				Norm-only			

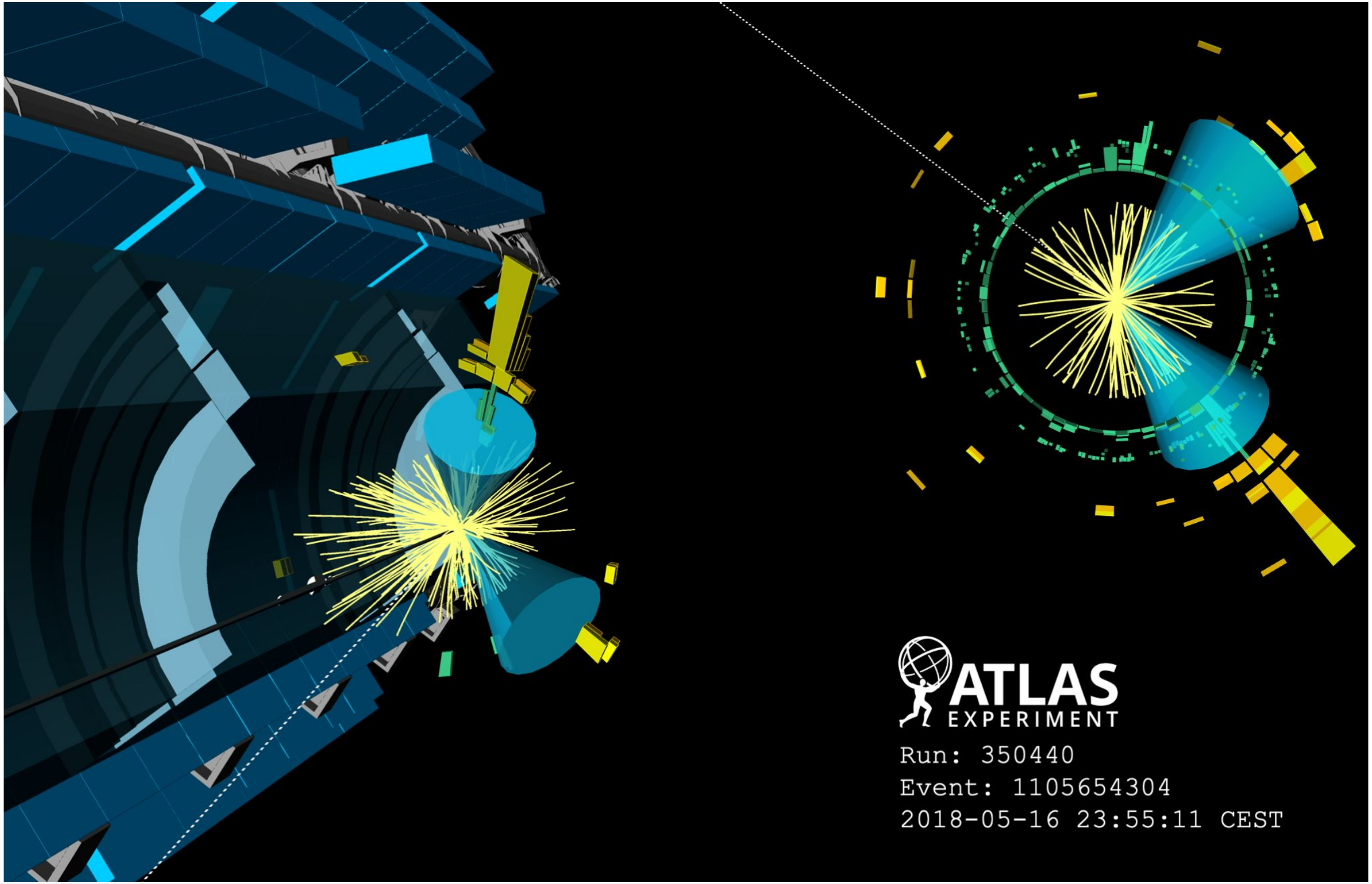
 # VH(cc) events expected (in the SM)

Candidate event display: 0L



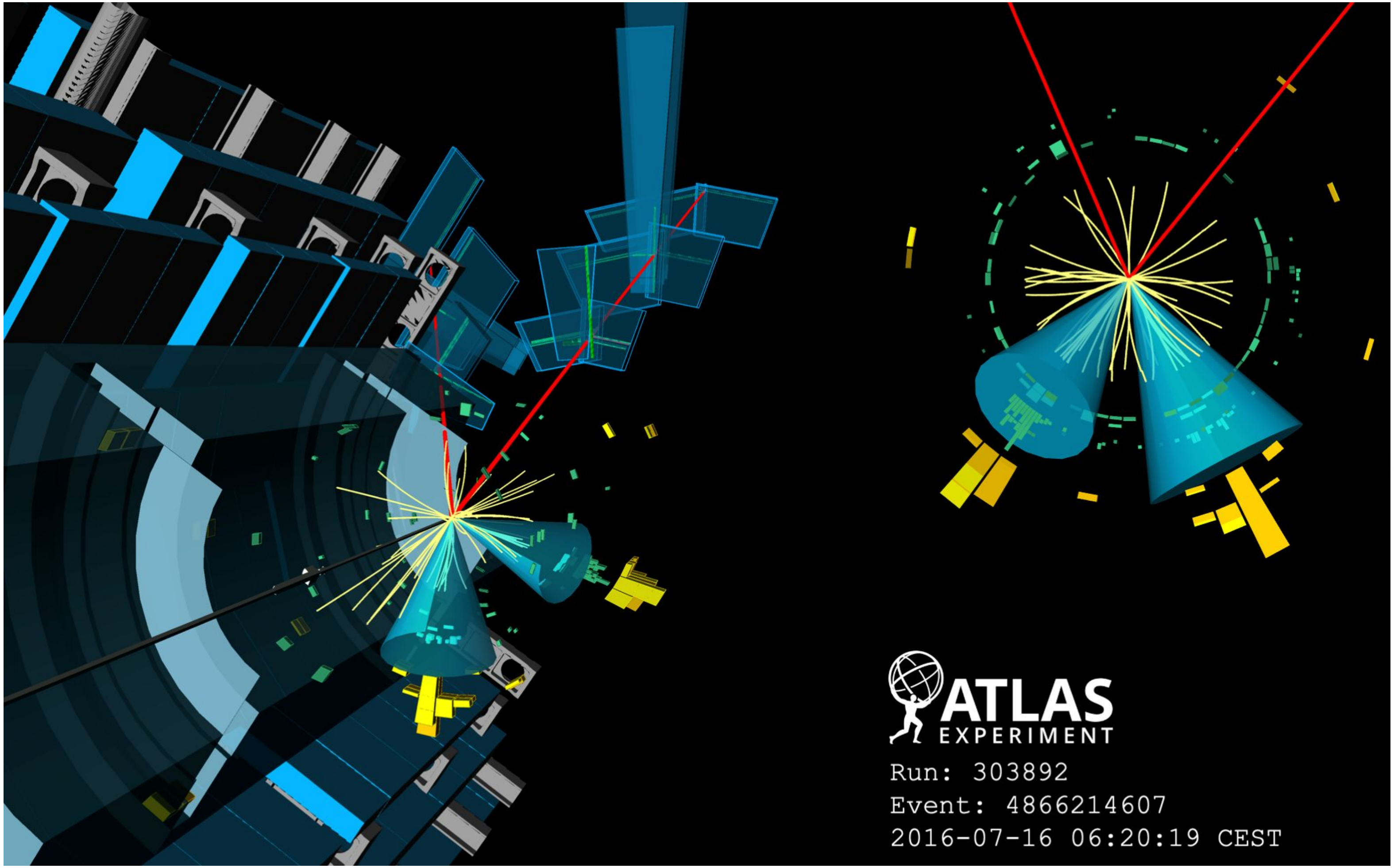
2 c-tag
m(cc) = 125 GeV

Candidate event display: 1L



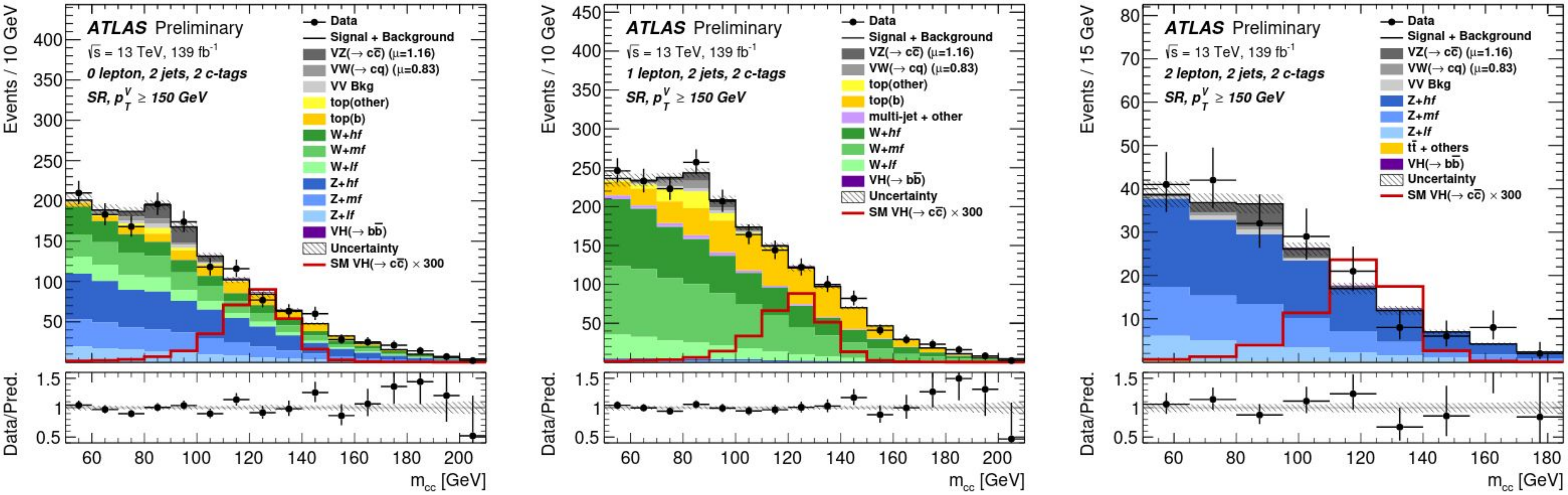
2 c-tag
m(cc) = 124 GeV

Candidate event display: 2L



2 c-tag, high $p_T(V)$
m(cc) = 123 GeV

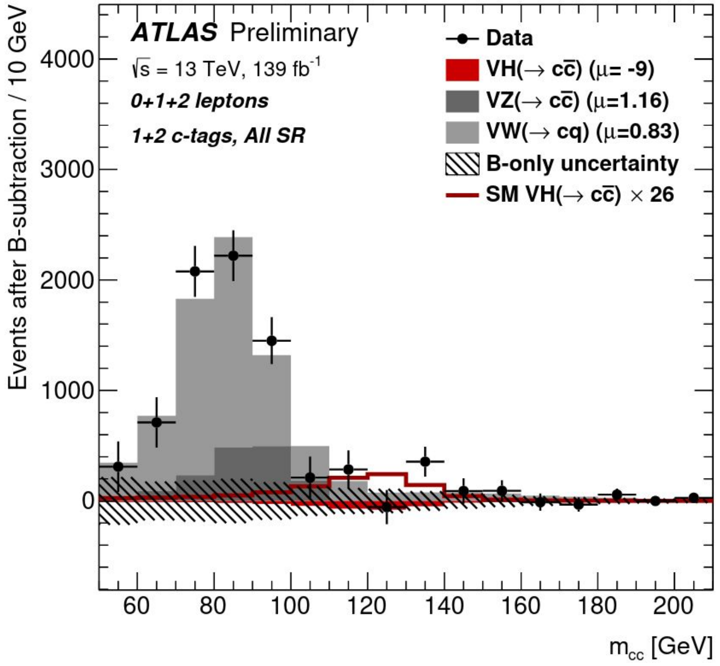
Postfit m(cc) distributions



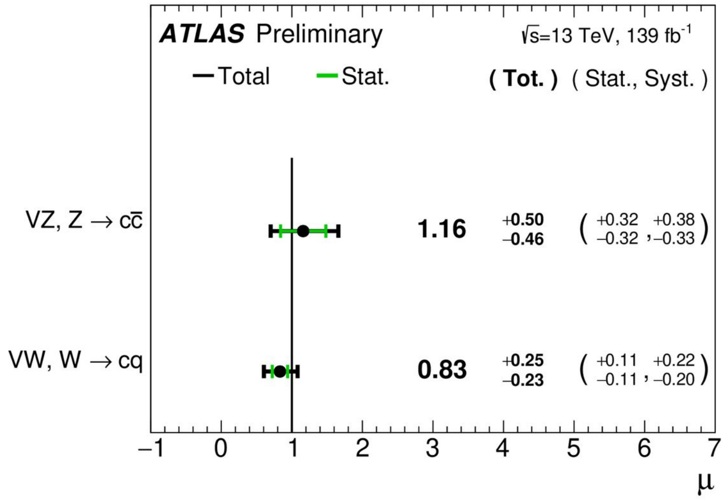
Most sensitive signal regions

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

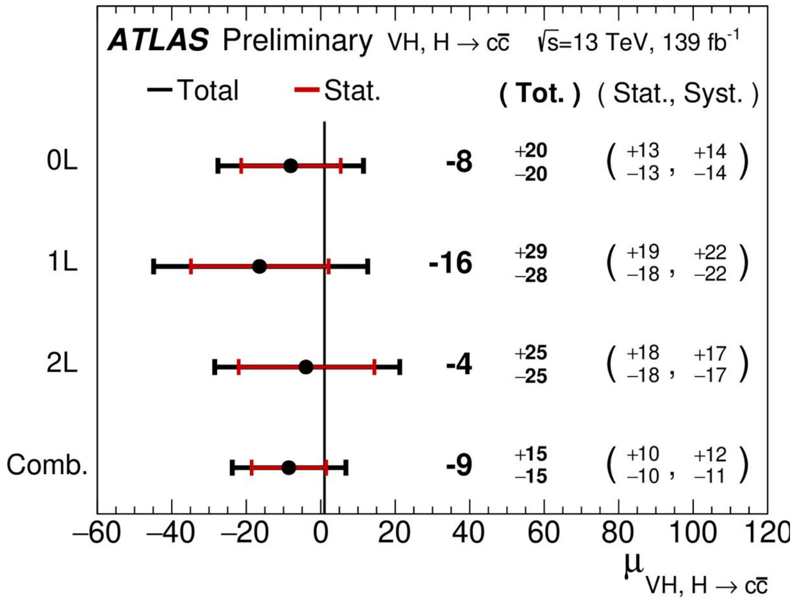
$\boldsymbol{\mu_{V(H \to cc)}}$ **= -9 ± 10 (stat.) ± 12 (syst.)**

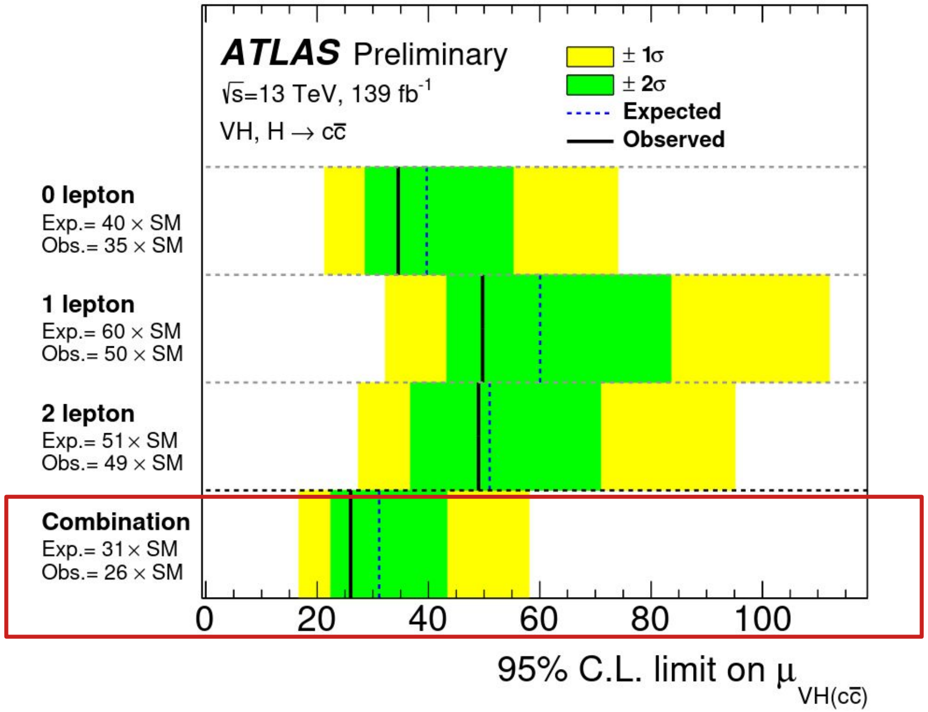
Compatibility with the SM: 84%

First "measurement" of VW/VZ using c-tagging

Good agreement with SM prediction
⇒ validation of VH(→ cc) search strategy

More $VH(\to cc)$ results





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

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

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

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.

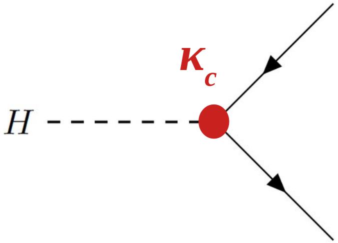
Dominant systematic uncertainty: *Z*+jets modelling

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

Interpretation of the result

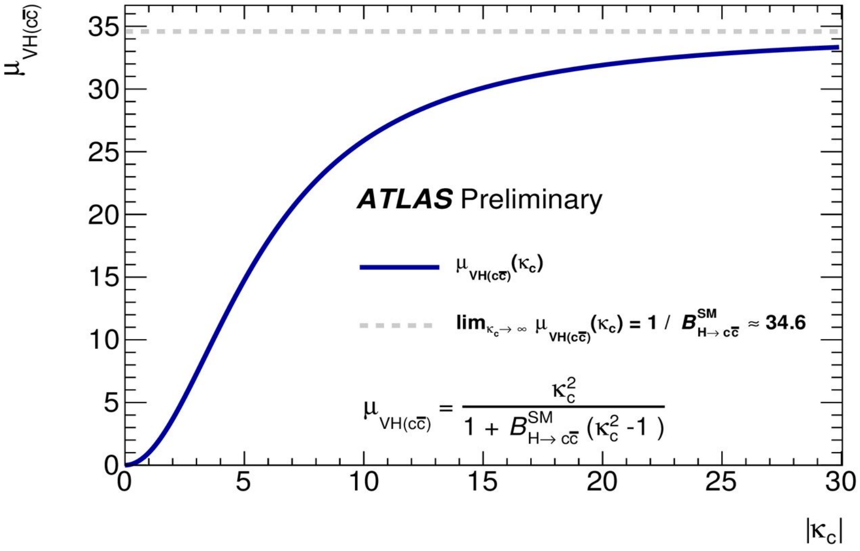
CERN-2013-004 (2013)

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



Higgs-charm coupling modifier

$\kappa_c = 1$ in SM



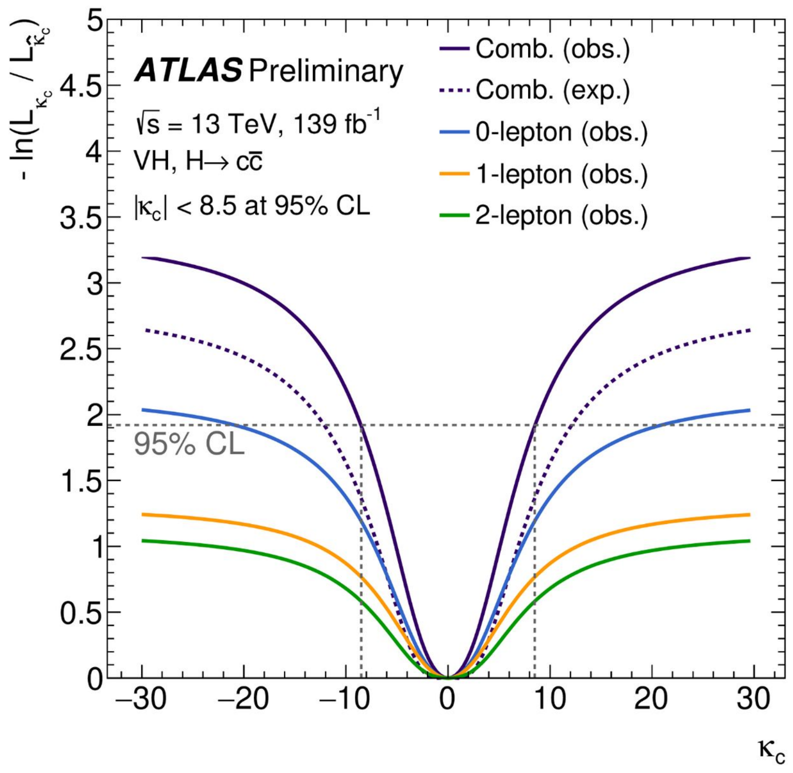
- Modification of the partial decay width by κ_c^2
- Modification of the total Higgs-boson total width, assuming
  - Only decays to SM particles
  - All other coupling-strength modifiers are 1

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

Parametrisation

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

$VH(\to cc)$: κ_c constraint



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

First direct constraint on κ_c!

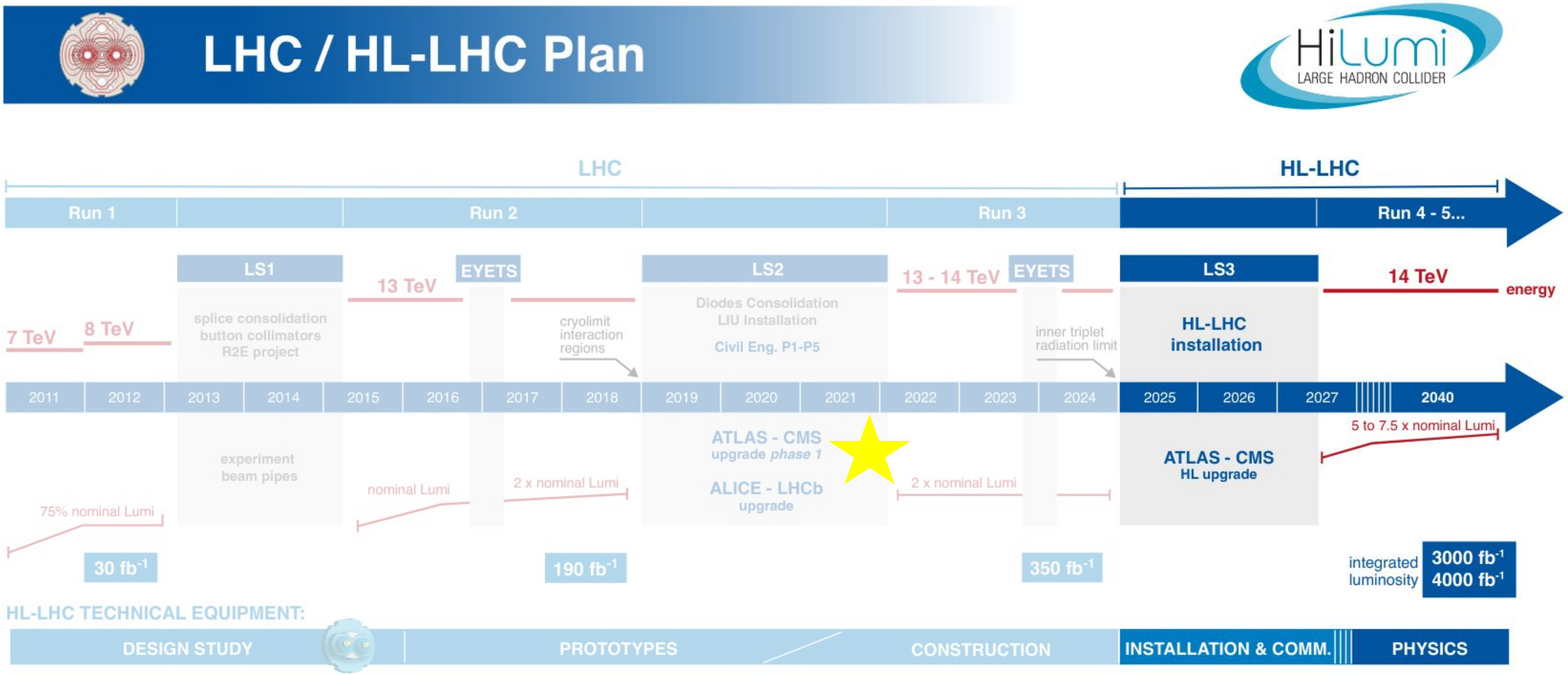
@68% CL: $|\kappa_c| < 3.5$ (4.9) obs. (exp.)

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

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

The High-Luminosity LHC (HL-LHC)

We're here



Source

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

Assumptions for the extrapolation of the full Run-2 analysis

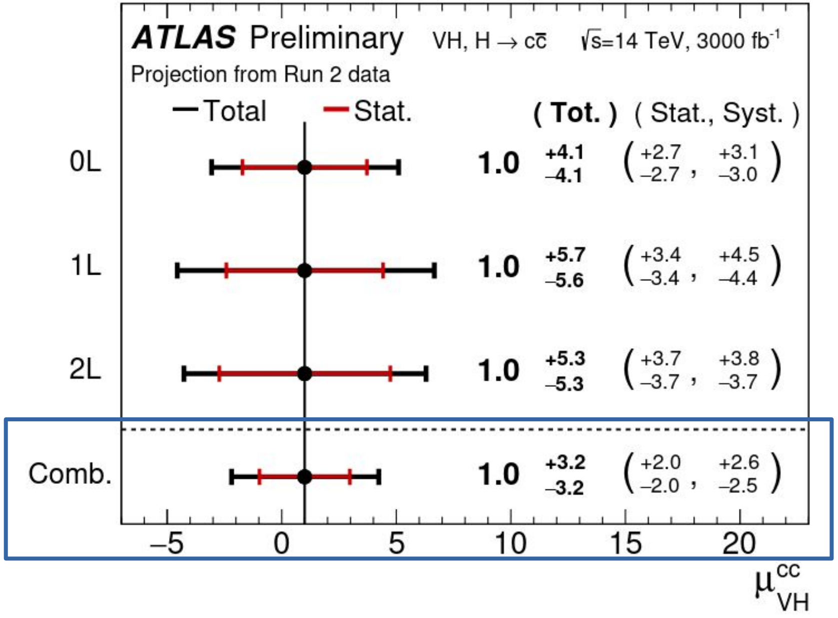
- Luminosity increase: ×~22
- Flat CoM cross-section scaling: ×1.10-1.18
- **Reduction of most systematic uncertainties by 50%**

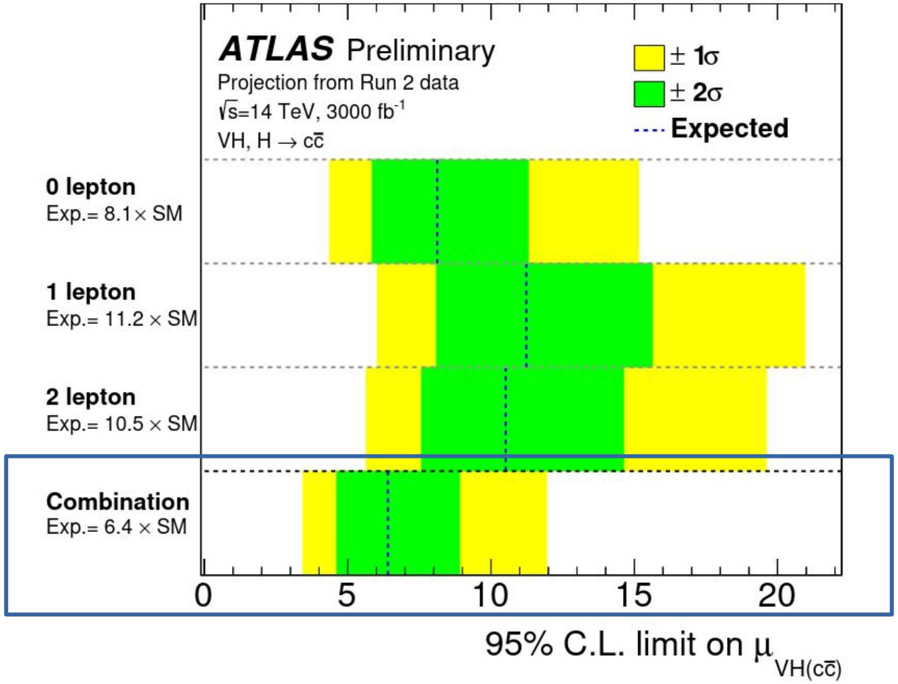
Uncertainties	Scale Factor
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.5
Lepton	1
Jet	1
Flavour tagging c-, b- and τ-jets	0.5
Flavour tagging light-jets (MV2c10 in $VH(bb)$)	0.5
Flavour tagging light-jets (DL1 in $VH(cc)$)	1.0
Luminosity	0.58
Signal modelling	0.5
Background modelling	0.5
MC statistics	0
Truth-tagging uncertainties ($VH, H \rightarrow c\bar{c}$ only)	0

$qq \rightarrow WH\ (H \rightarrow c\bar{c}/b\bar{b})$	1.10
$qq \rightarrow ZH\ (H \rightarrow c\bar{c}/b\bar{b})$	1.11
$gg \rightarrow ZH\ (H \rightarrow c\bar{c}/b\bar{b})$	1.18
$t\bar{t}$ $gg \rightarrow ZZ$	1.16
$qq \rightarrow VV$ V+jets single top	1.10

- **Uncertainties due to limited simulated sample sizes: negligible (!)**

$VH(\to cc)$ @ the HL-LHC - Results





⇒ **systematic uncertainties are of similar size** on the combined signal

0L remains the most sensitive channel

⇒ **systematic uncertainties dominating in 0/1L**

Uncertainties breakdown and alternative scenarios

Nikhef

Source of uncertainty		$\Delta\mu_{VH}^{c\bar{c}}$
Total		3.21
Statistical		1.97
Systematics		2.53
Statistical uncertainties		
Data statistics only		1.59
Floating normalisations		0.95
Theoretical and modelling uncertainties		
$VH, H \to c\bar{c}$		0.27
Z+jets		1.77
Top-quark		0.96
W+jets		0.84
Diboson		0.34
$VH, H \to b\bar{b}$		0.29
Multi-Jet		0.09
Experimental uncertainties		
Jets		0.59
Leptons		0.20
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.18
Pile-up and luminosity		0.19
Flavour tagging	c-jets	0.61
	b-jets	0.16
	light-jets	0.51
	τ-jets	0.19

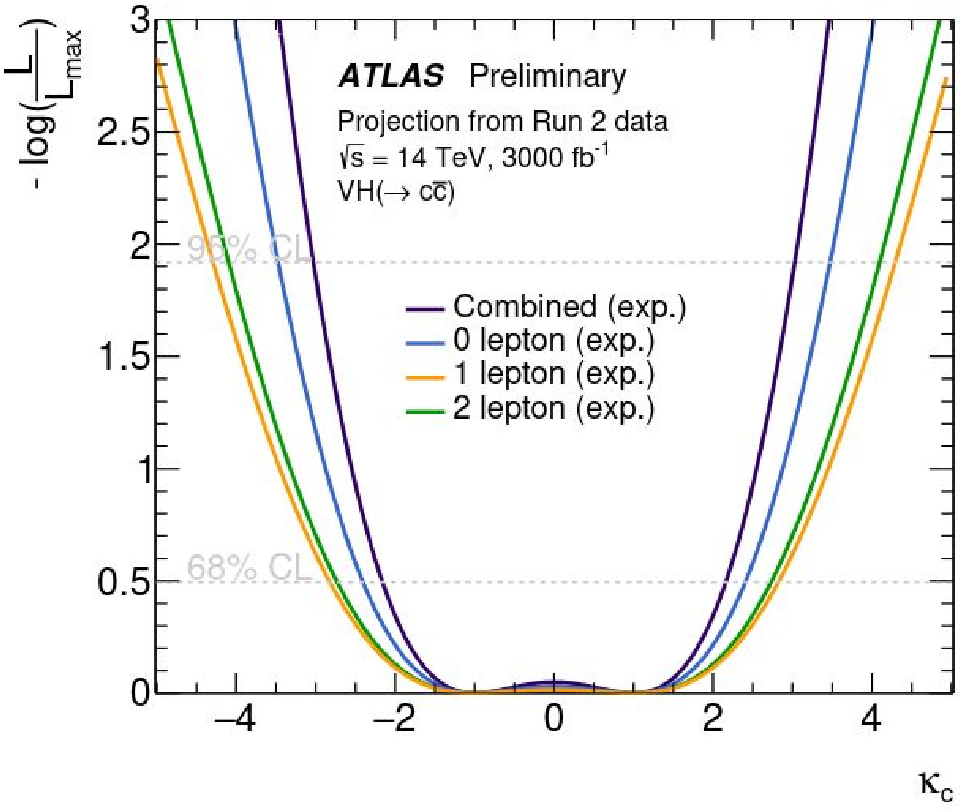
single largest contribution

Alternative scenarios ⇒ impact on expected limit

- **Signal/background modelling unc. ×2/0.5: -/+10%**
  (×2: no improvement wrt. Run-2)
- Including truth-flavour tagging unc.: - 4%
- Including MC statistical unc. - assuming they improve as the luminosity: - 5%
- **Improved b-(light)-jet rejections** by ×1.5 (3) thanks to the inner detector upgrade (ITk): **+10-15%**
  (With the same DL1c tagger)

Preliminary!

VH(→*cc*) @ the HL-LHC: κ_c constraint



Expected constraints:

@68% CL: $|\kappa_c| < 2.2$

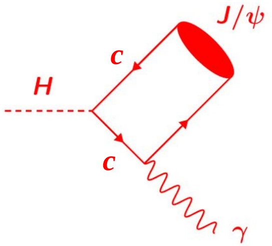
@95% CL: $|\kappa_c| < 3.0$

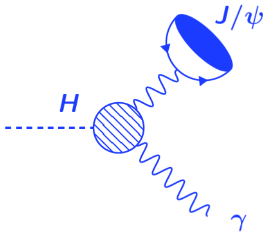
Complementary approaches (attempts?) to constrain the Higgs-charm coupling

Exclusive $H \to J/\Psi\gamma$ decays

Phys. Lett. B 786 (2018) 134

- First proposed in arXiv:1505.03870; BR ~ $O(10^{-6})$
- Pro: does not require c-tagging; sensitive to ***sign*** **and** ***magnitude*** **of** κ_c
- Cons: **destructive interference** of two amplitudes:





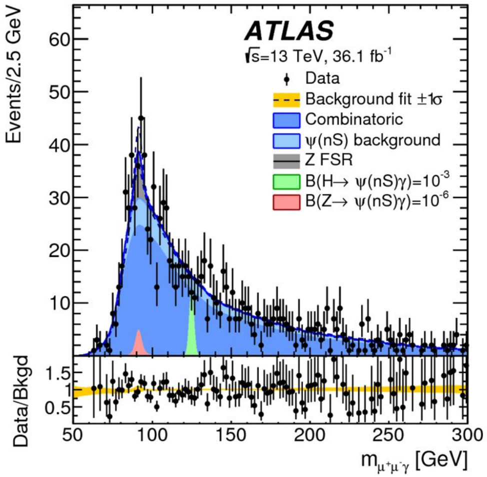
From A. Chisholm

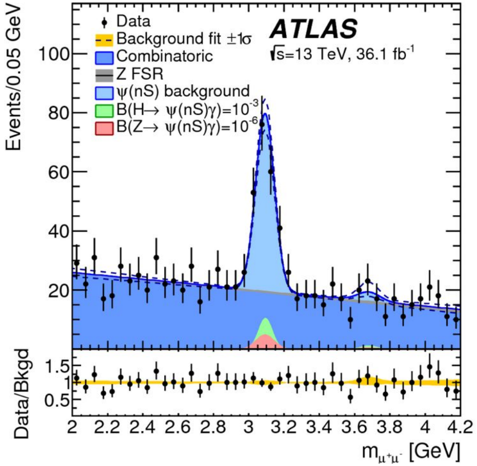
$H \to cc$: sensitive κ_c **$H \to \gamma\gamma$: dominant (×10 larger)**

→ **Sensitivity to κ_c diluted**

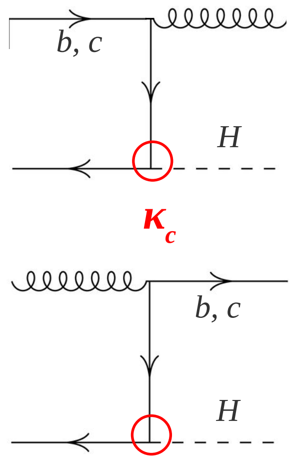
Search pioneered by ATLAS in Run 1; updated measurement on partial Run-2 dataset

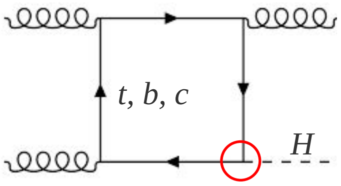
- **Obs. (exp.) upper limit on BR($H \to J/\Psi\gamma$) @95% C.L.: 117 (100) × SM**
- **No κ_c interpretation**





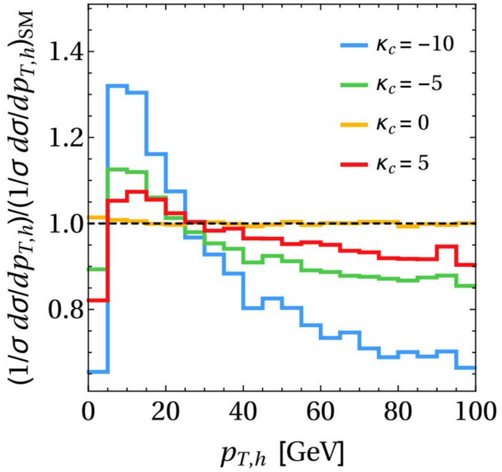
p_T(H) spectrum





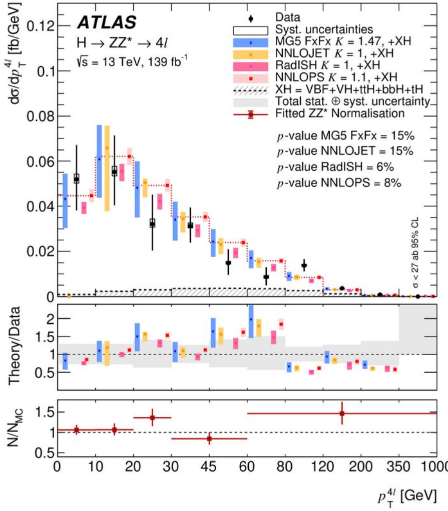
First proposed in [Phys. Rev. Lett. 118 (2017) 121801]

- The p_T(H) spectrum is sensitive to modifications of the *sign* and *magnitude* of κ_c (and κ_b) in the **production**
  - Pro: does not require *c*-tagging
  - Cons: indirect (more assumptions)



Approach applied to full Run-2 p_T(H) **differential cross-section measurements** in

- ***$H \rightarrow ZZ^* \rightarrow 4l$*** [Eur. Phys. J. C 80 (2020) 942]
- ***$H \rightarrow \gamma\gamma$*** [ATLAS-CONF-2019-029]



⇒ κ_c interpretation (simultaneously with *κ_b*)

(Same assumptions as before: only decays to SM particles are allowed, all other $\kappa = 1$)

κ interpretation from $p_T(4l)$ spectrum

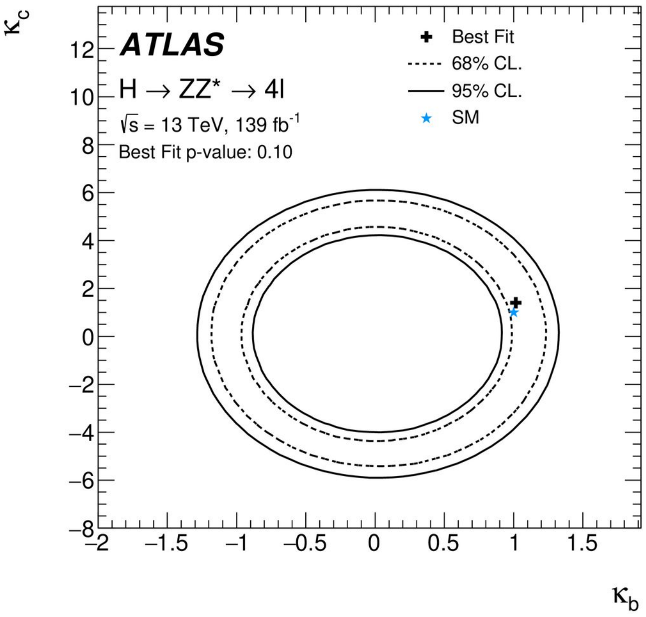
Increasing model-dependence

Improving constraint

Interpretation	Parameter best fit value	95% Confidence Interval
Modifications to only $p_T^{4\ell}$ shape	$\kappa_c = -1.1$	$[-11.7, 10.5]$
	$\kappa_b = 0.28$	$[-3.21, 4.50]$
Modifications to $p_T^{4\ell}$ predictions	$\kappa_c = 0.66$	$[-7.46, 9.27]$
	$\kappa_b = 0.55$	$[-1.82, 3.34]$

Modifications affecting

...only the *production*



...the *production*
and *the total width* (→ *BR*)

Reminder

V(H → cc) $[\kappa_b = 1]$

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

***Direct* and *indirect* constraints are comparable!**

Detailed comparison difficult

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
- HL-LHC extrapolation results promising
  - Significant work to reduce (modelling) uncertainties necessary
- Measurements of $p_T(H)$ spectra in $H\rightarrow 4l$ (and $H\rightarrow \gamma\gamma$) provide **comparable *indirect* constraints on $\boldsymbol{\kappa_c}$**