Higgs boson coupling to second generation fermions with the ATLAS detector

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Higgs 2021 21/10/2021

Introduction

- **Coupling of Higgs boson to gauge bosons and 3rd generation fermions well-established**

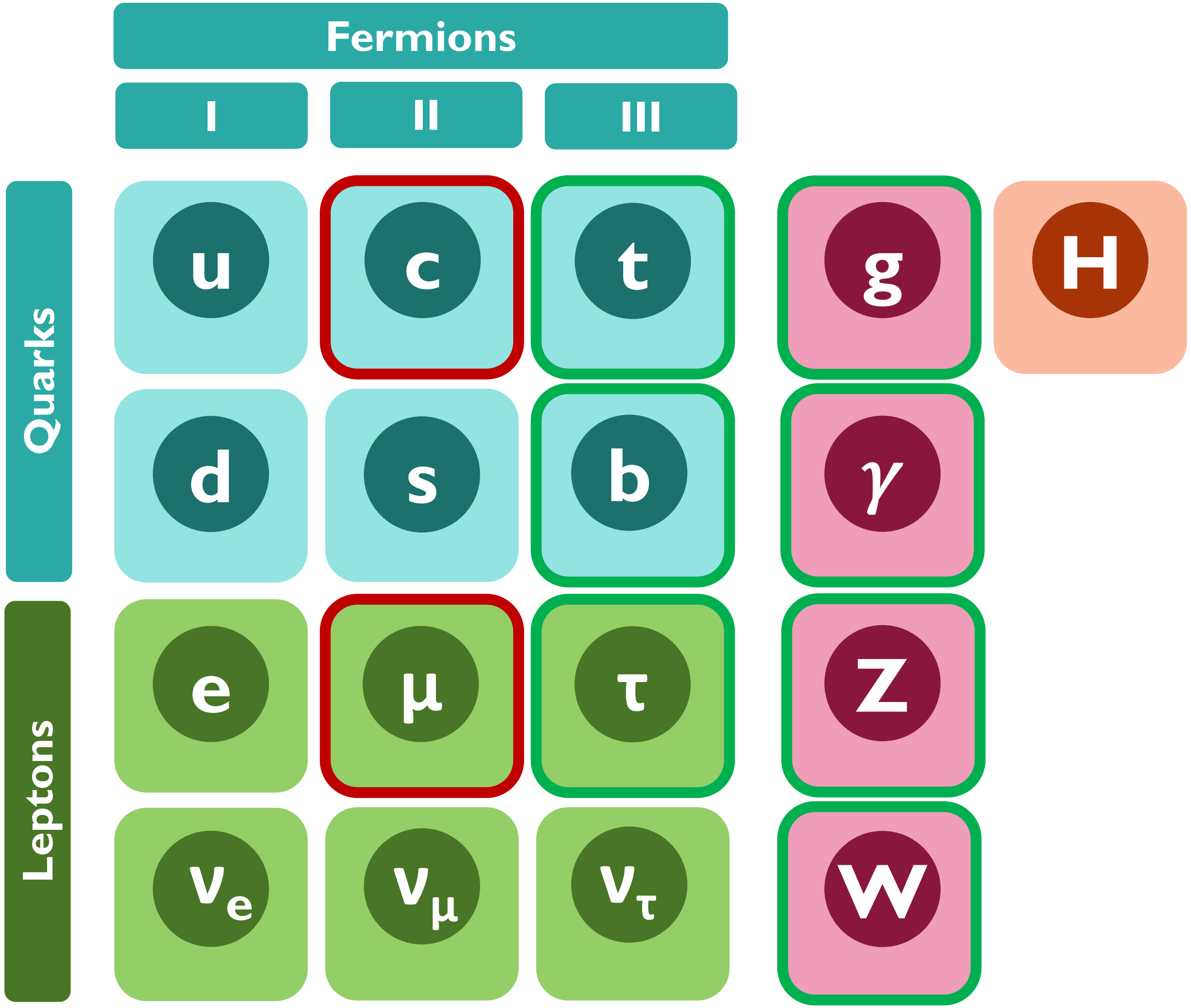
→ Good agreement with the Standard model

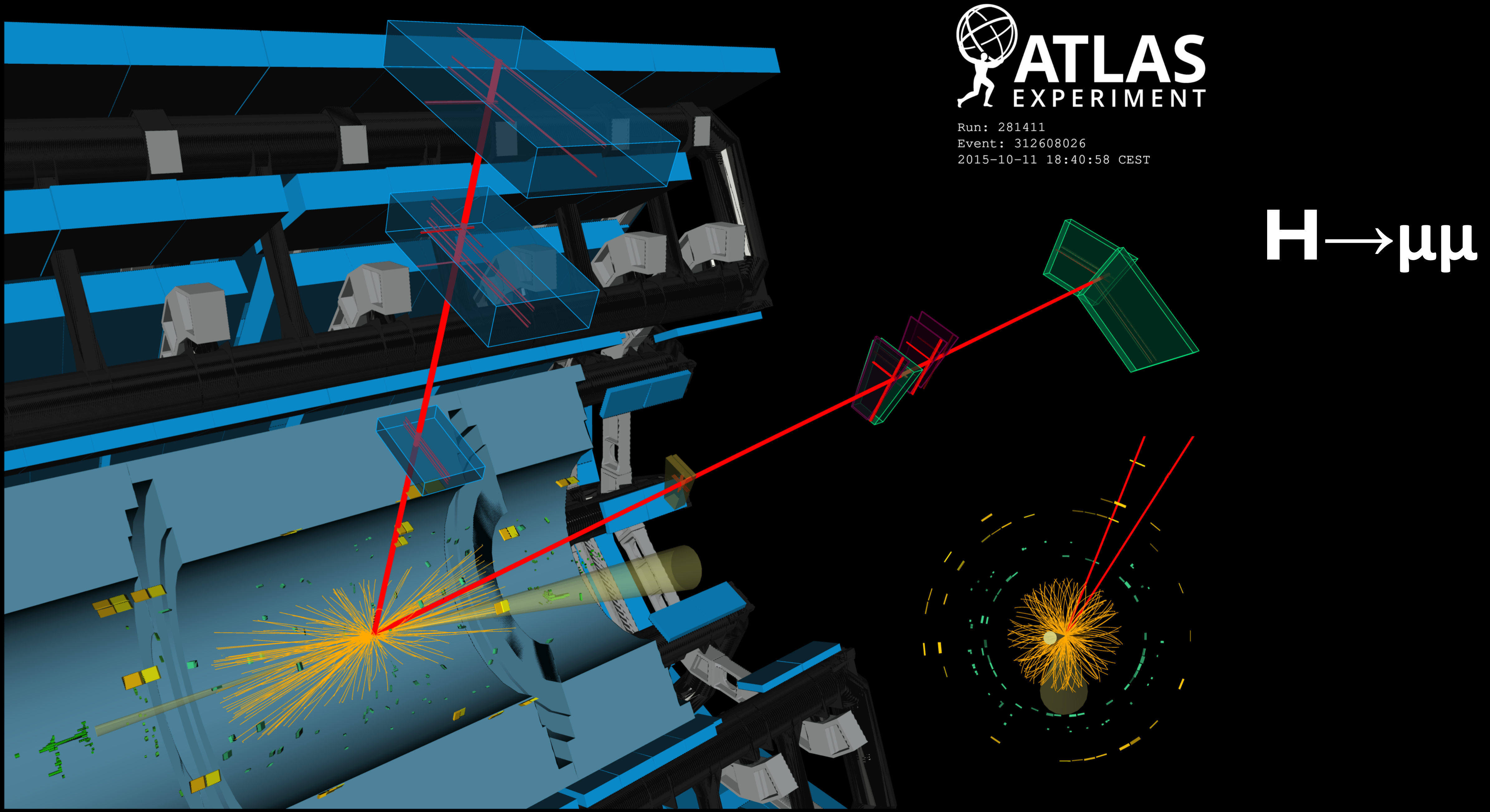
- No observation of coupling to 1st and 2nd generation so far

→ any deviation would indicate new physics

- **Next most promising measurements are couplings to muons and charm-quarks**

→ Use the ATLAS Full Run 2 dataset to improve our constraints




ATLAS
EXPERIMENT
Run: 281411
Event: 312608026
2015-10-11 18:40:58 CEST
H→μμ

Higgs coupling to muons

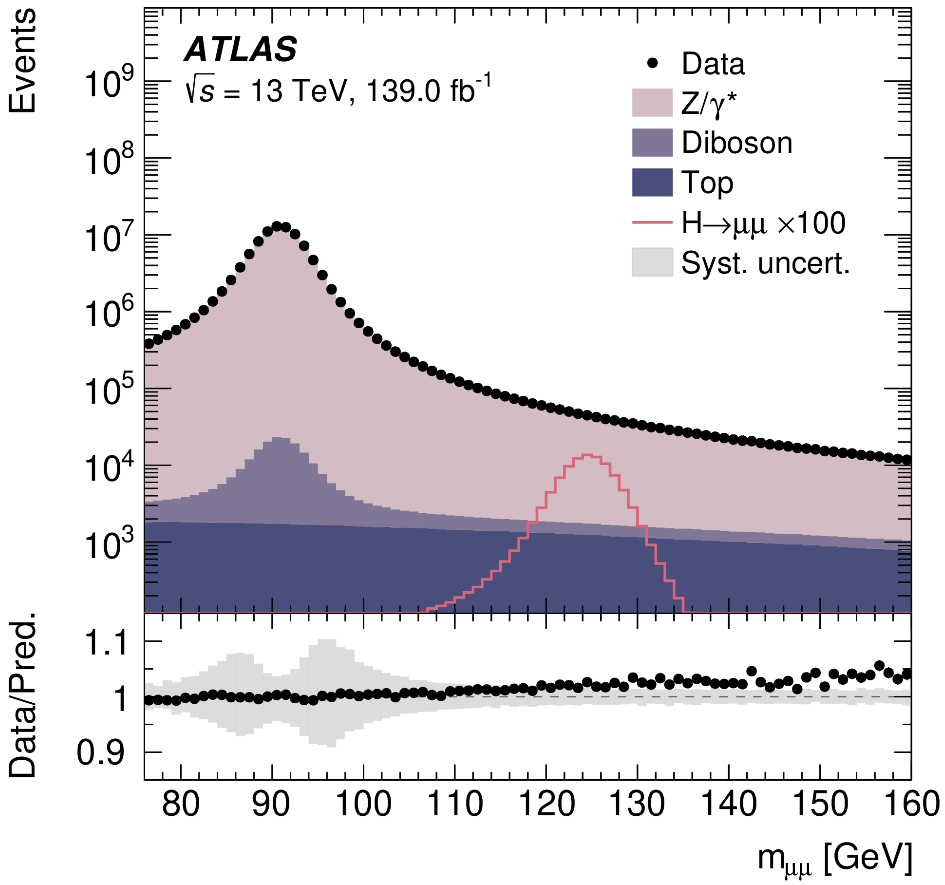
[Phys. Lett. B 812 (2021) 135980]

- **Direct probe of Higgs coupling to second generation**
- Good mass resolution $\sigma_m/m(\mu\mu) \sim 2\%$

Main experimental challenges:

- Rare process: branching ratio of $(2.17 \pm 0.04) \times 10^{-4}$
- Large background from Drell-Yan $\mu\mu$ production

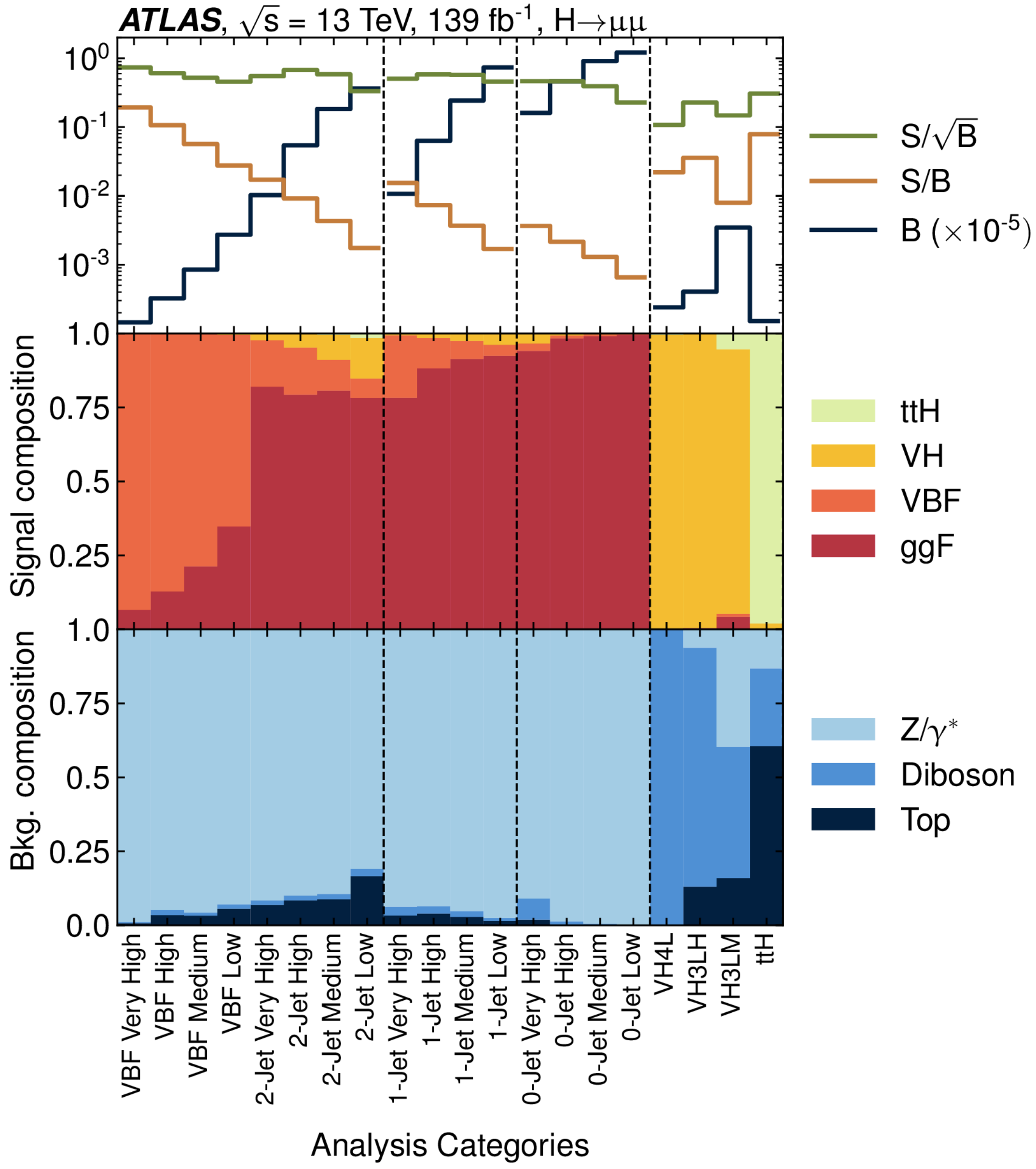
→ Signal-to-background ratio of ~0.2% in signal region (120-130 GeV)



Analysis strategy

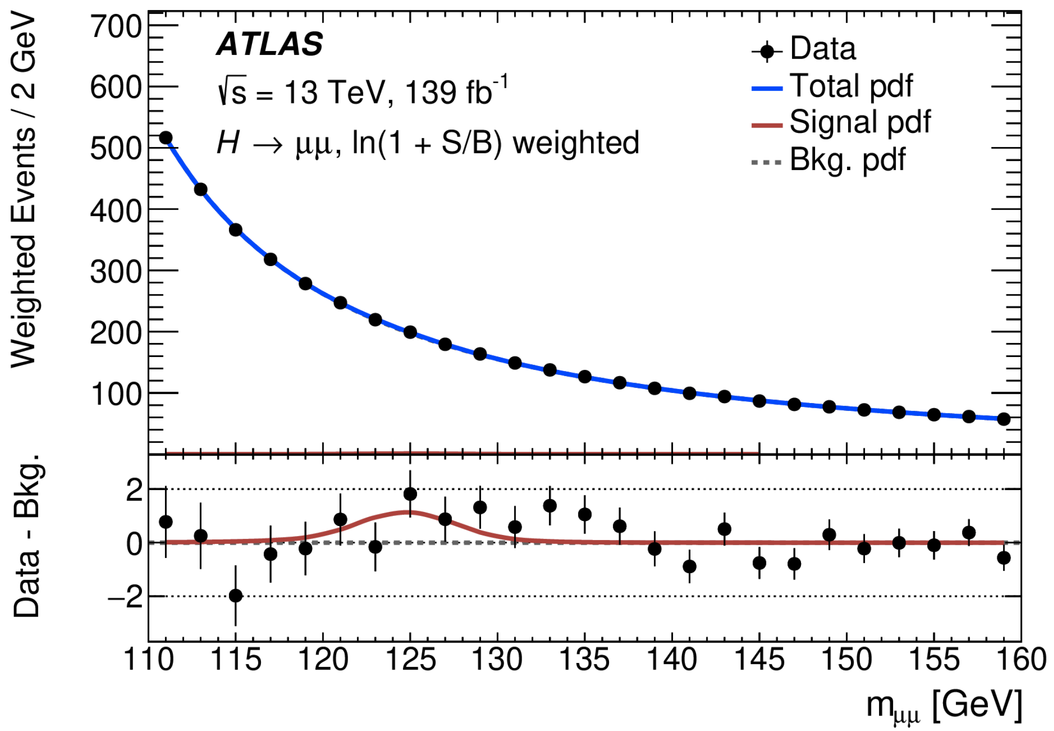
- Exploit multiple production modes: VBF, VH, ggF and ttH
- Sort events into 20 mutually exclusive categories, using process specific boosted decision trees:
  - Overall categories driven by kinematic criteria on jets/leptons
  - Then, MVA discriminants categorise signal and background → build sub-categories
- **S/B ranging from <0.1% to 18%**
- **Significance ranging from 0.1 to 0.6 σ**
- VBF and ggF most sensitive
- Drell-Yan background dominant for ggF/VBF categories & excellent background modelling is crucial:
  - Parametric function with rigid core (DY, corrected for detector resolution) + flexible part (to account for mismodelling and data/MC)

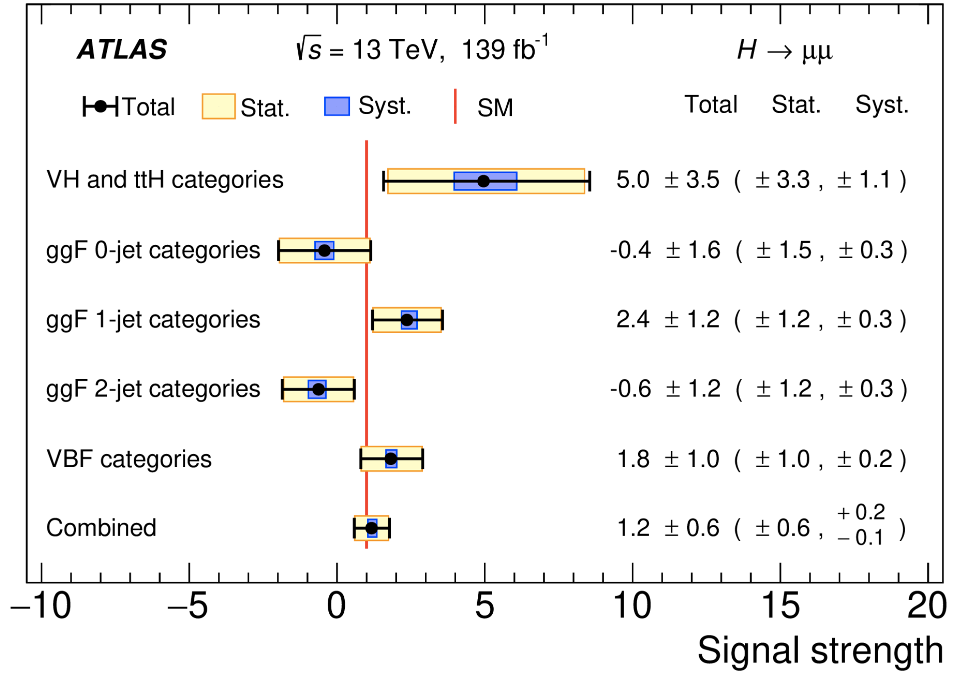
  → Reduces number of degrees of freedom in fit, while keeping spurious signal low



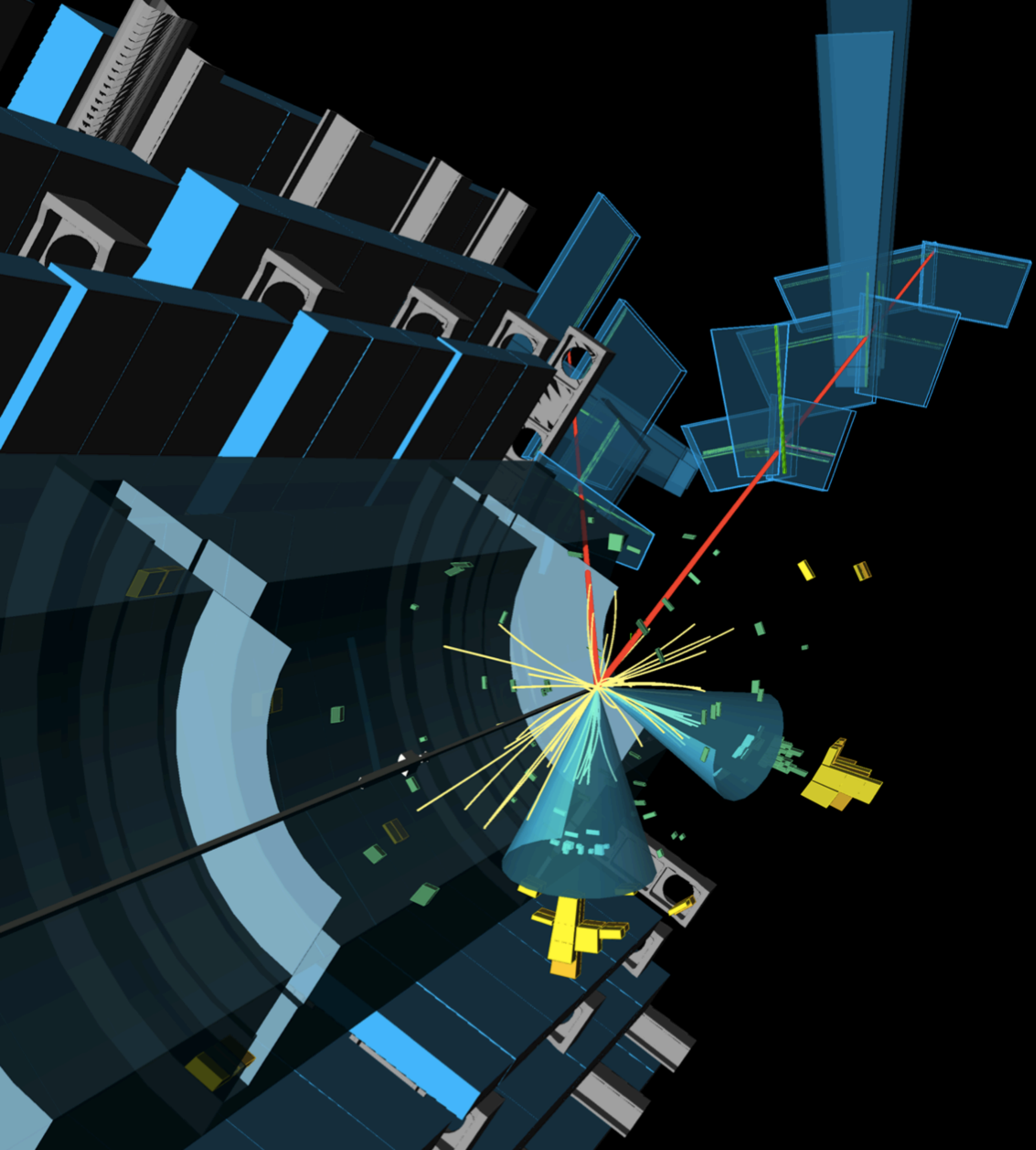
Results

- Fit to $m_{\mu\mu}$ performed between 110-160 GeV
- Signal modelling: double-sided crystal ball function
- Background modelling using empirical function





- Best fit signal strength: **1.2 ± 0.6**
- Observed BR limit at 95% CL: <4.7 x 10^{-4}
- Significance: **2.0σ** (1.7σ) **observed** (expected)
- Uncertainties dominated by data statistics, followed by signal theory uncertainties
- Large improvement over previous publication due to larger dataset and analysis improvements

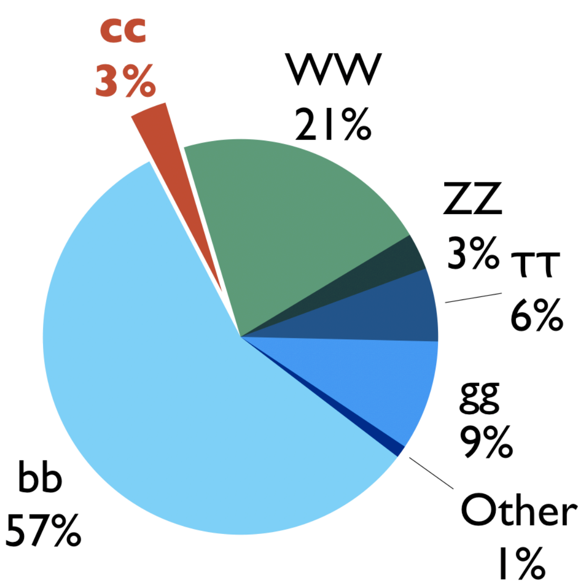


H→cc

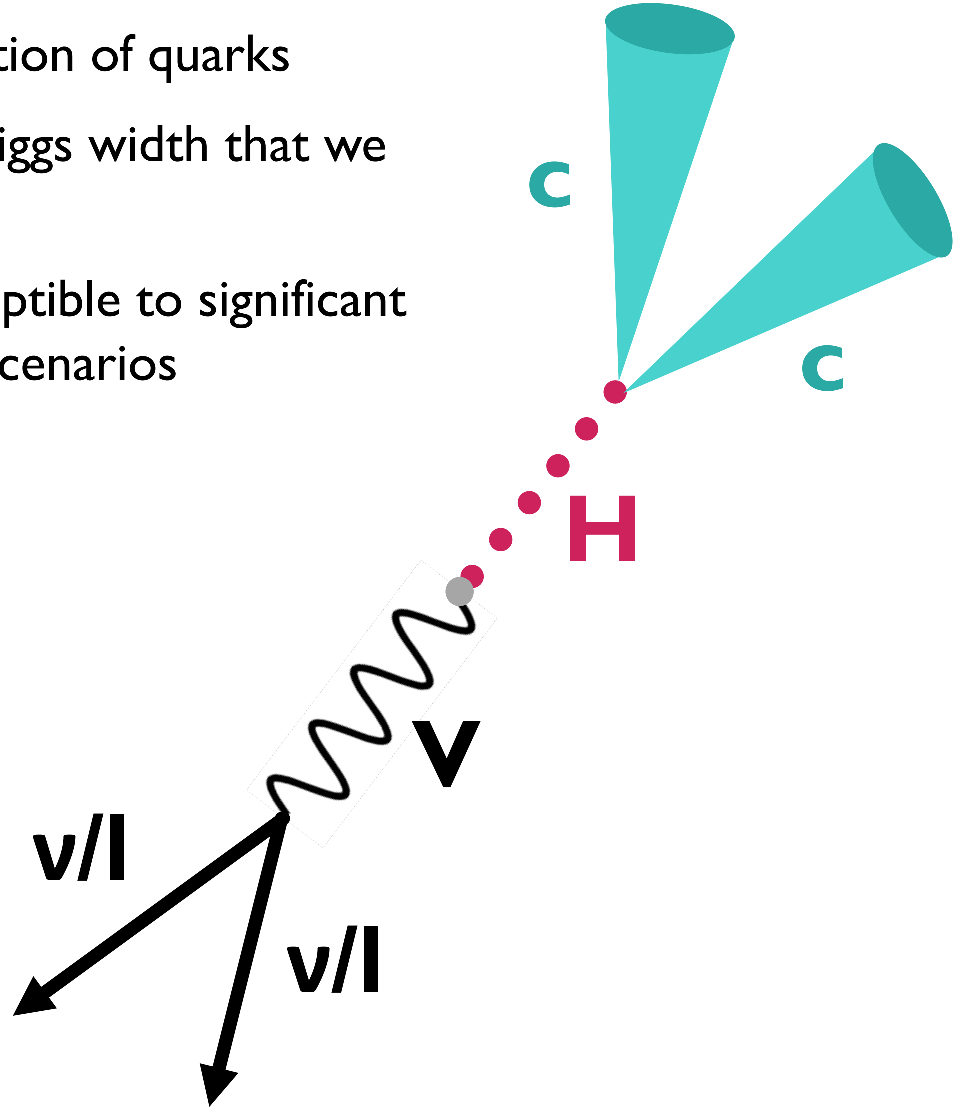
ATLAS EXPERIMENT

Run: 303892
Event: 4866214607
2016-07-16 06:20:19 CEST

Higgs coupling to charm quarks



- Probe of Higgs coupling to 2nd generation of quarks
- One of the largest contributions to Higgs width that we have no evidence for
- Small charm Yukawa coupling → susceptible to significant modifications in various new physics scenarios
- Search in VH production mode
- Categorisation into channels by the decay of the vector boson:
  - 0 lepton: Z(νν)H(cc)
  - 1 lepton: W(lν)H(cc)
  - 2 lepton: Z(ll)H(cc)

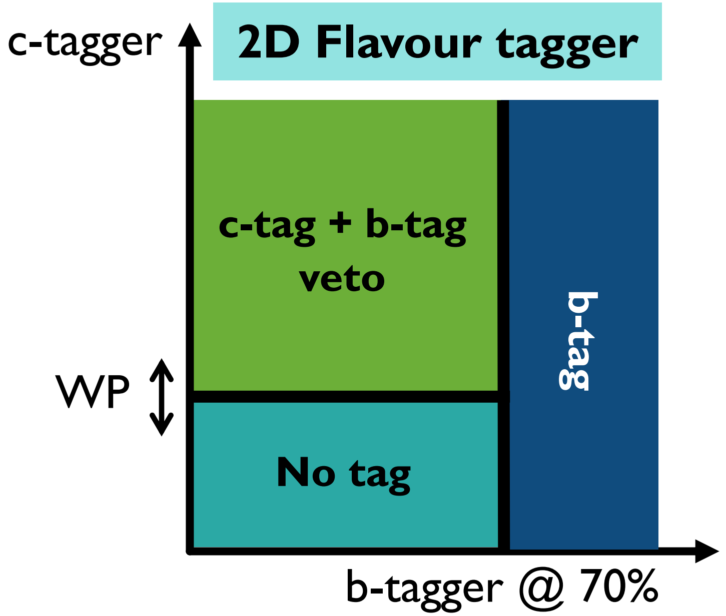


Indirect constraints from H→J/Ψγ on Higgs-charm coupling
Indirect constraints from H→ϕγ on Higgs-strange coupling

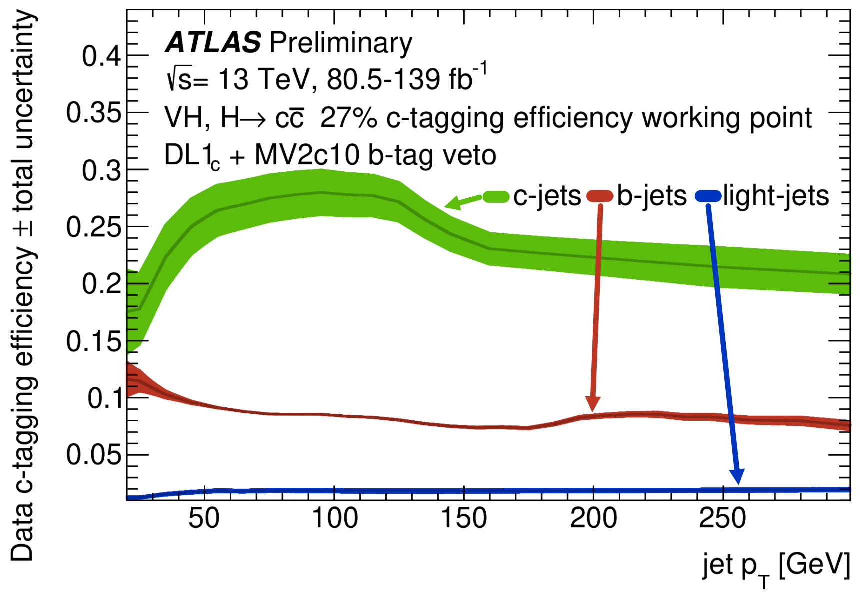
Analysis strategy

- Further event categorisation by transverse momentum of vector boson, jet multiplicity and 1 or 2 c-tags
- Flavour tagging: **Identification of c-jets and orthogonality to the VH(bb) analysis**
- c-tagging + b-veto working point (WP):
  - dedicated c-tagger for the VH(cc) analysis
  - b-veto using the b-tagging strategy of the VH(bb) analysis
- Dedicated optimisation and calibration of WP:
  - **c-jets (27%), b-jets (8.3%), light-jets (1.7%)**
- **Cut-based analysis:** m_{cc} of two leading p_T jets as a discriminant
- Simultaneous binned likelihood fit to the signal strength of VH(cc), VZ(cc) and VW(cq)

2D Flavour tagger



Efficiency for the calibrated WP



Signal regions

Discriminant: m_{cc} of the two leading p_T jets

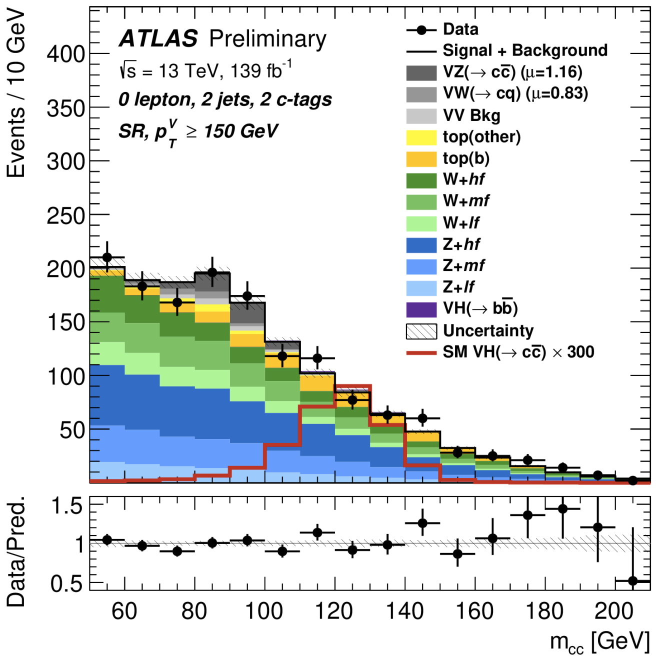
Signal: **VH(cc)**, **VZ(cc)**, **VW(cq)**

Major backgrounds: **W+jets**, **Z+jets**, **Top** → Constrained in dedicated control regions

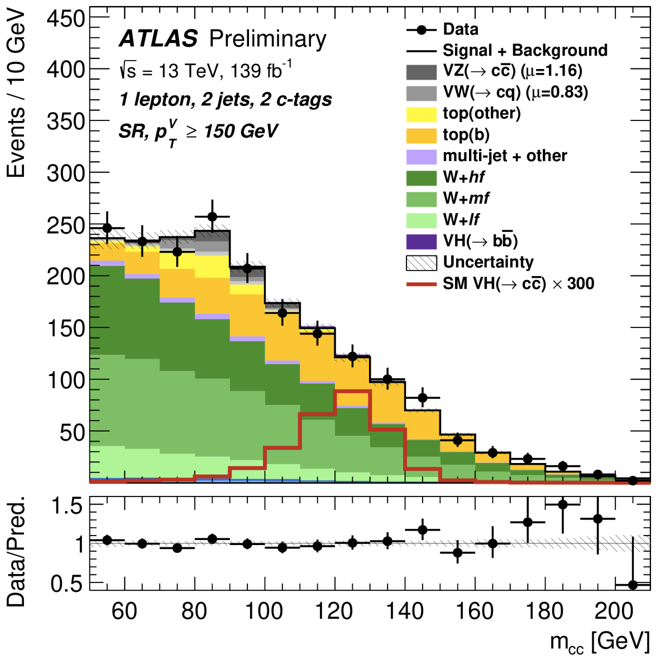
Subdominant backgrounds: **VH(bb)**, **VV background**

2 c-tag

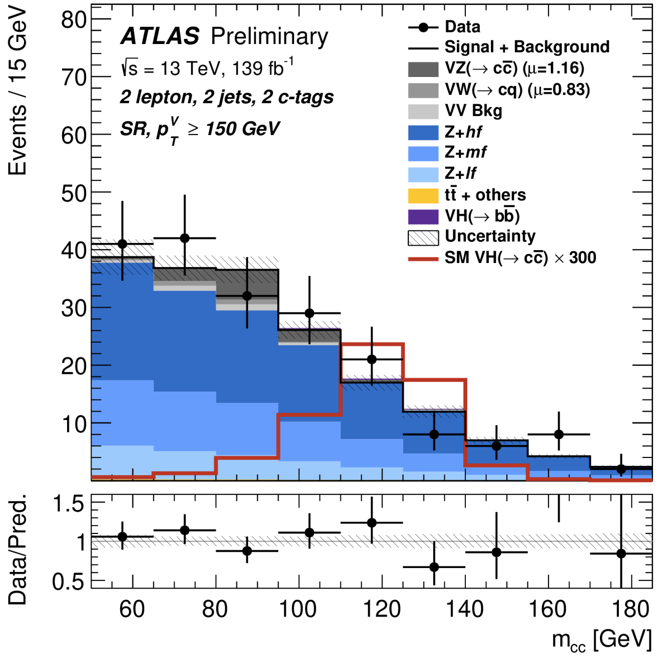
0 lepton



1 lepton

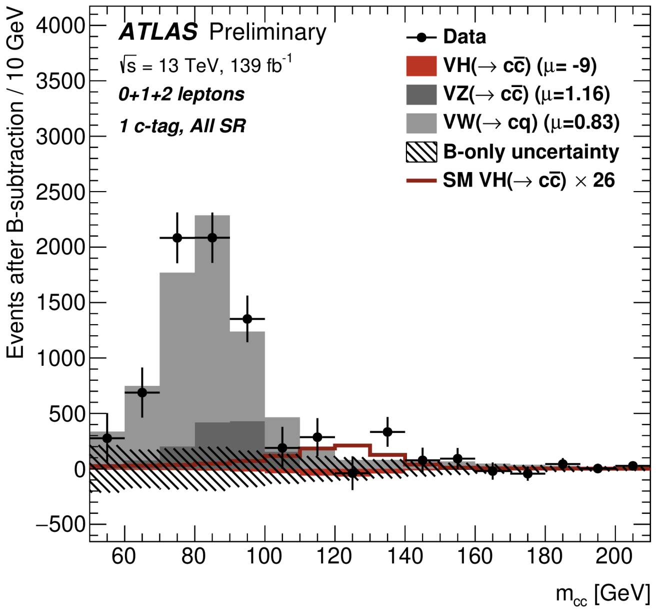


2 lepton

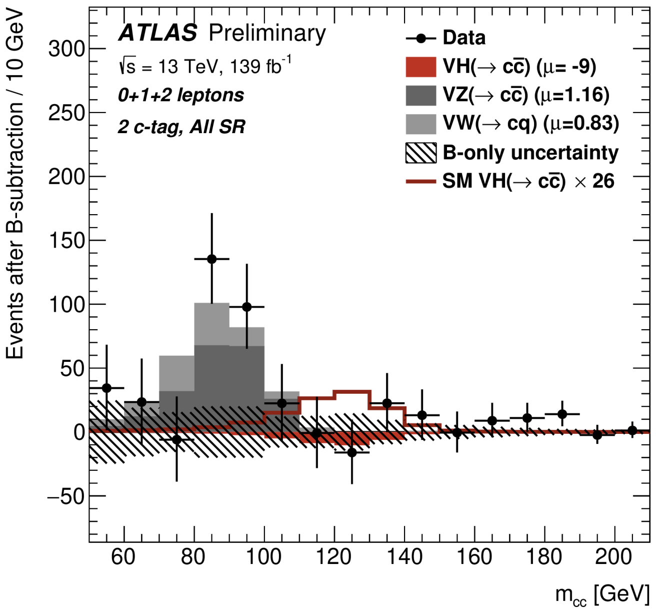


Mass distributions

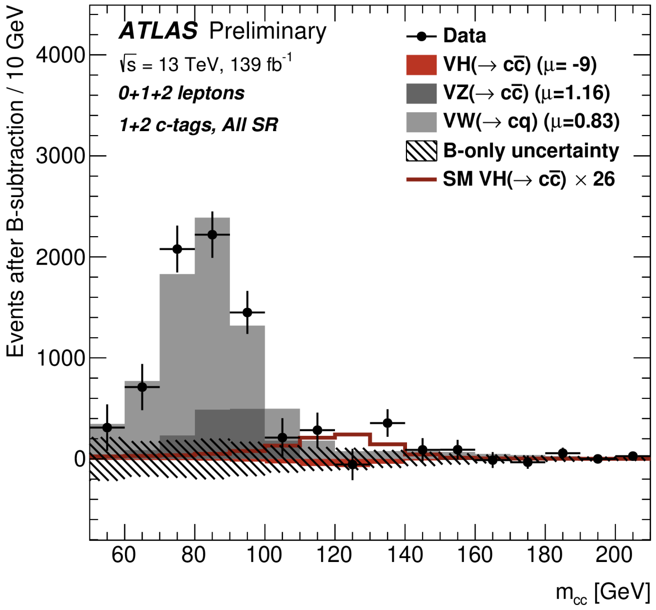
1 c-tag



2 c-tag



1+2 c-tag

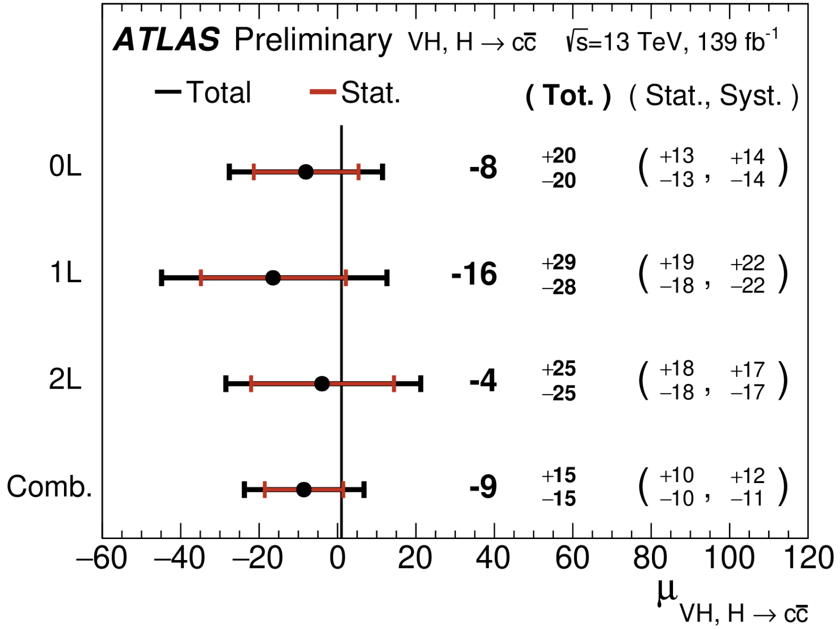


- m_{cc} distributions with backgrounds subtracted → good data/simulation agreement
- Diboson cross-checks measurements:
  - VW(cq) significance of **3.8σ** (4.6σ expected)
  - VZ(cc) significance of **2.6σ** (2.2σ expected)

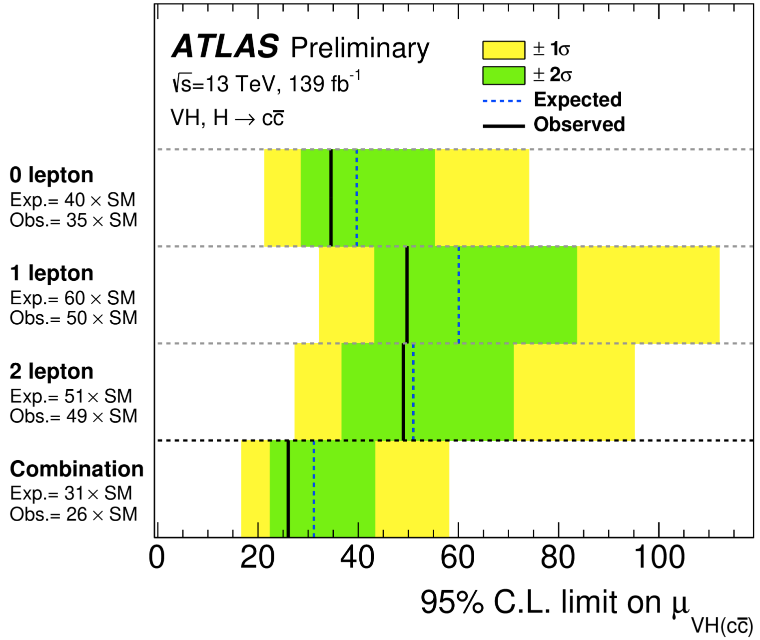
→ First measurements of VZ(cc) and VW(cq) using c-tagging!

Signal strengths and limits

Best fit signal strength for VH(cc)



95% CL limits on $\mu_{VH(cc)}$



- Best fit signal strength $\mu_{VH(cc)}$ = -9 ± 15 → compatibility with SM: 83.9%
  - Statistical and systematic uncertainties of similar size
  - Leading systematics: V+jets/top modelling and flavour tagging
- Observed VH(cc) limit of **26 x SM** (31 x SM expected) → **best limit on VH(cc) yet!**

κ_c interpretation

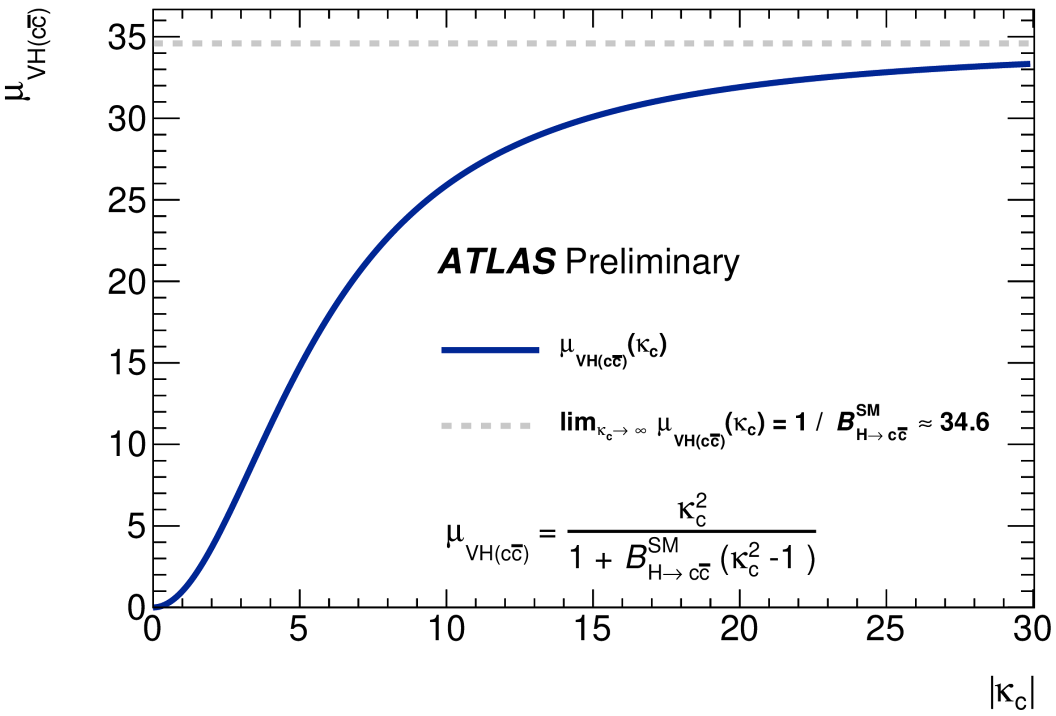
- Possible to reparametrise signals strength in terms of κ_i coupling modifiers
- Considering modifications to decay only
- Signal strength parameterised as:

$$\mu(\kappa_i) = \frac{\kappa_c^2}{B(H \to c\bar{c})\kappa_c^2 + (1 - B(H \to c\bar{c}))}$$

(other coupling modifiers set to 1)

- Implicitly assuming no contributions from BSM decays to Higgs width with this parametrisation
- Only sensitive to κ_c in this parametrisation if limit on $\mu<35$, assuming all other contributions to Higgs width are SM-like

Signal strength parameterisation as a function of κ_c

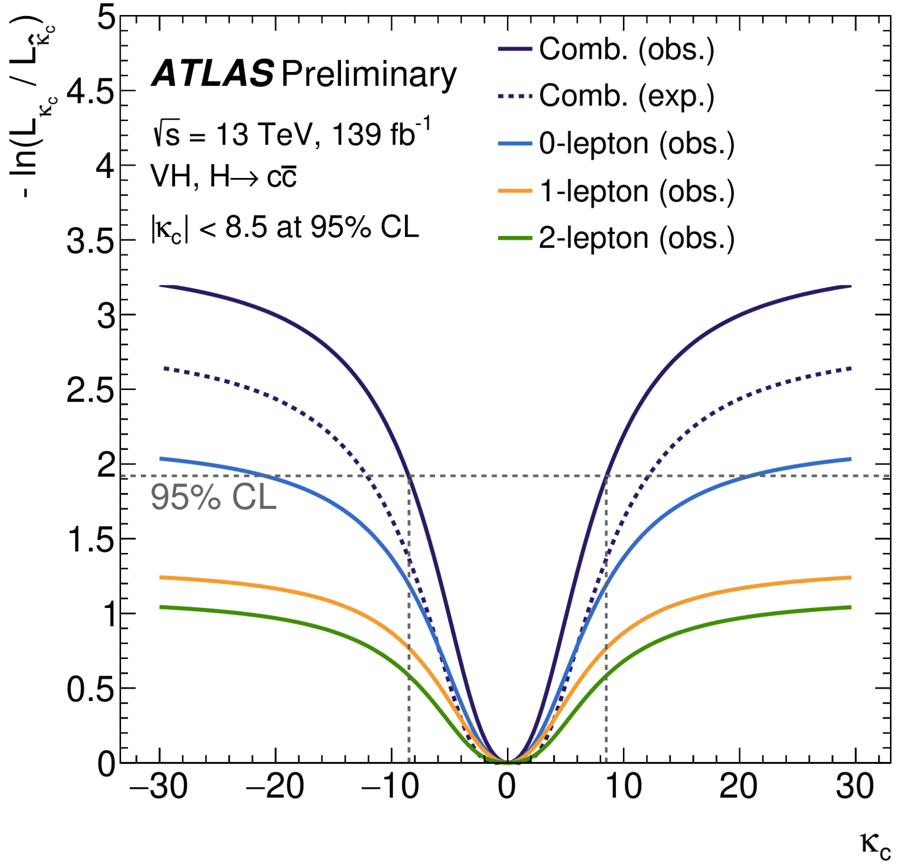


κ_c interpretation

- Expected limit on κ_c at 95% CL in combined fit $|\kappa_c| < 12.4$
- Observed best fit $\kappa_c = 0$
- **First direct limit on κ_c @ 95%CL with $|\kappa_c| < 8.5$**

	95% CL limit
Expected	[-12.3, 12.4]
Observed	[-8.5, 8.5]

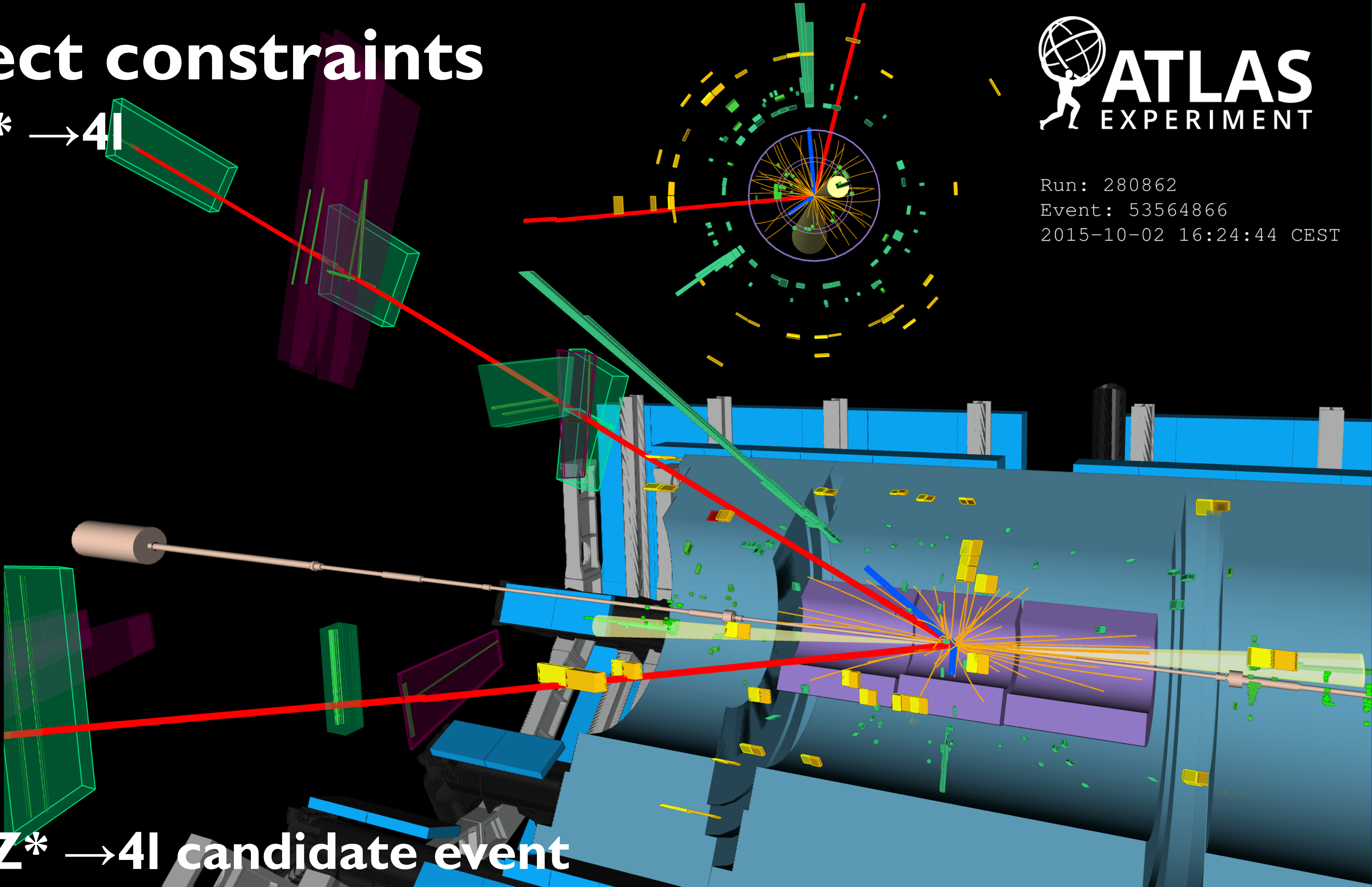
Likelihood scan of κ_c



Indirect constraints

$H \rightarrow ZZ^* \rightarrow 4l$

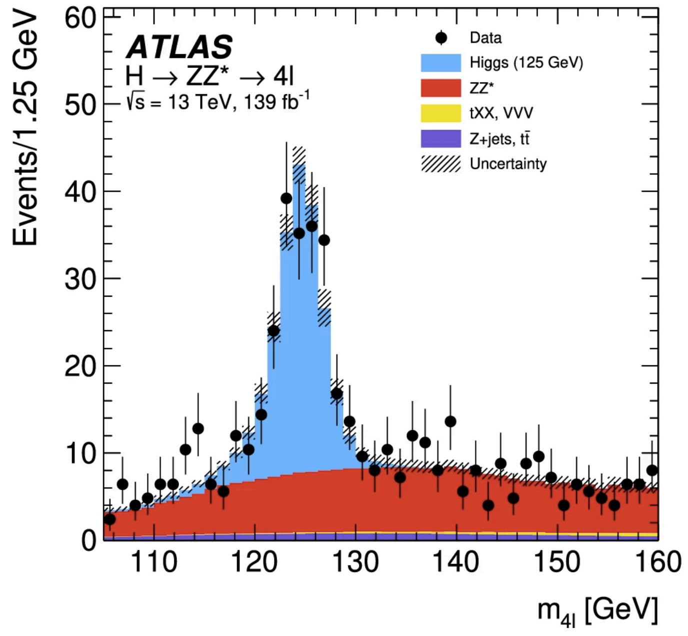
$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ^* \rightarrow 4l$ candidate event

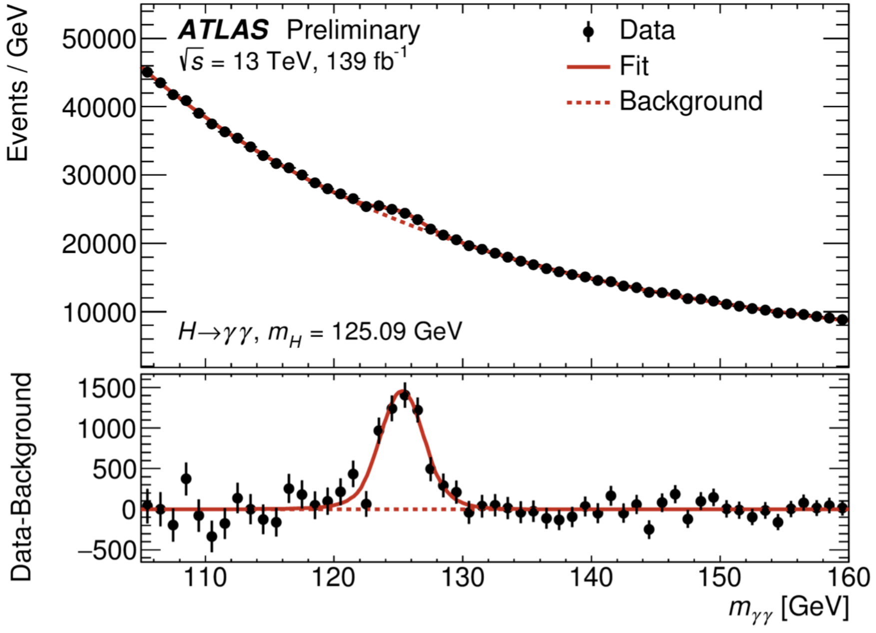
Precision measurements

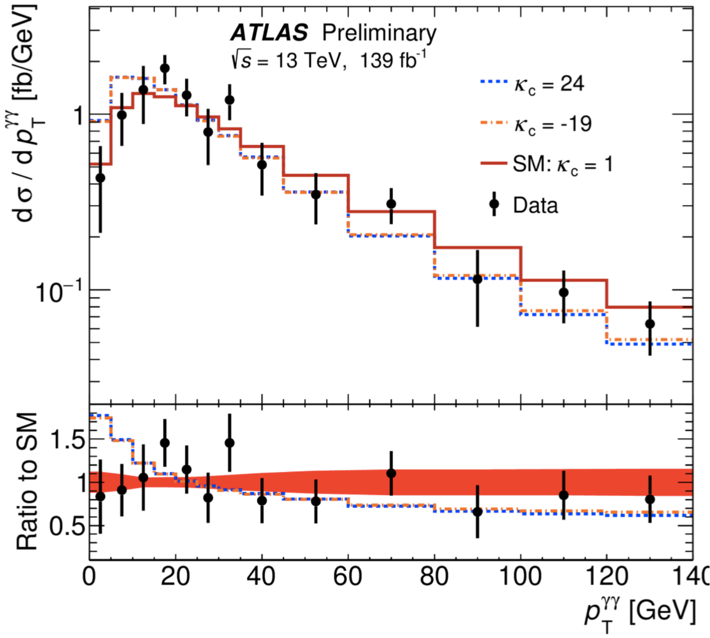
- High-precision Higgs measurements in the [H→$\gamma\gamma$] and [H→ZZ* →4l] channels
- Fit to invariant mass $m_{\gamma\gamma}$ or m_{4l}
- Inclusive and differential cross-section measurements
- H→$\gamma\gamma$ and H→ZZ* →4l can be sensitive to κ_c and κ_b through quark loop contributions to Higgs production



- Impact on shape and normalisation of the p_T^H spectrum

→ Can be constrained in differential measurements





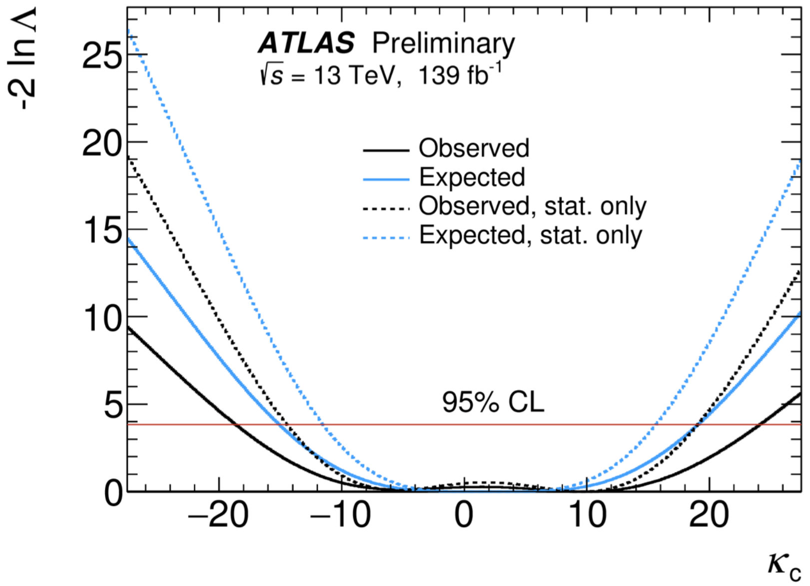
Indirect constraints

- $H \to \gamma\gamma$: considering only p_T^H shape to set constraints on κ_c, assuming κ_b and $\kappa_t = 1$
- $H \to ZZ^* \to 4l$: 1) Considering only p_T^H shape to set constraints on κ_c and κ_b

  2) Considering both p_T^H shape and normalisation, w/ additional assumptions → best constraining power

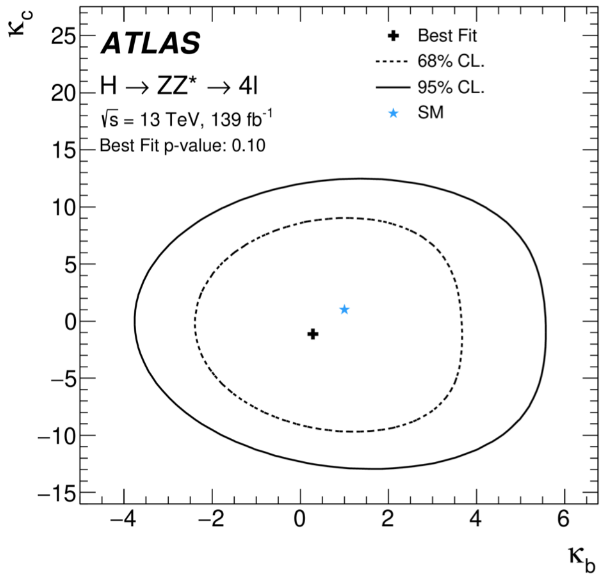
→ Limitations are complementary to H→cc, excellent pairing towards constraining the Hcc coupling with ATLAS data

$H \to \gamma\gamma$, p_T^H shape-only



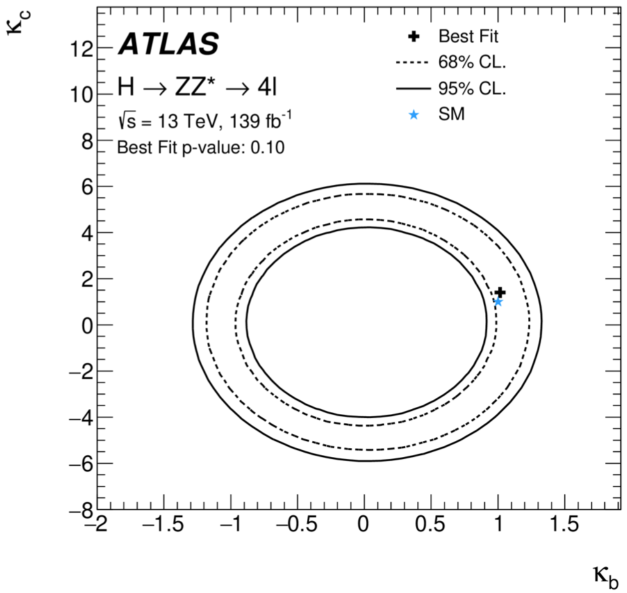
$-19 < \kappa_c < 24$

$H \to ZZ^* \to 4l$, p_T^H shape-only



$-11.7 < \kappa_c < 10.5$

$H \to ZZ^* \to 4l$, p_T^H shape & norm



$-7.5 < \kappa_c < 9.4$

Conclusions

- Presented latest ATLAS Run 2 results of the Higgs couplings to second generation fermions

H→μμ:

- 2.0σ observed significance (for 1.7σ expected)

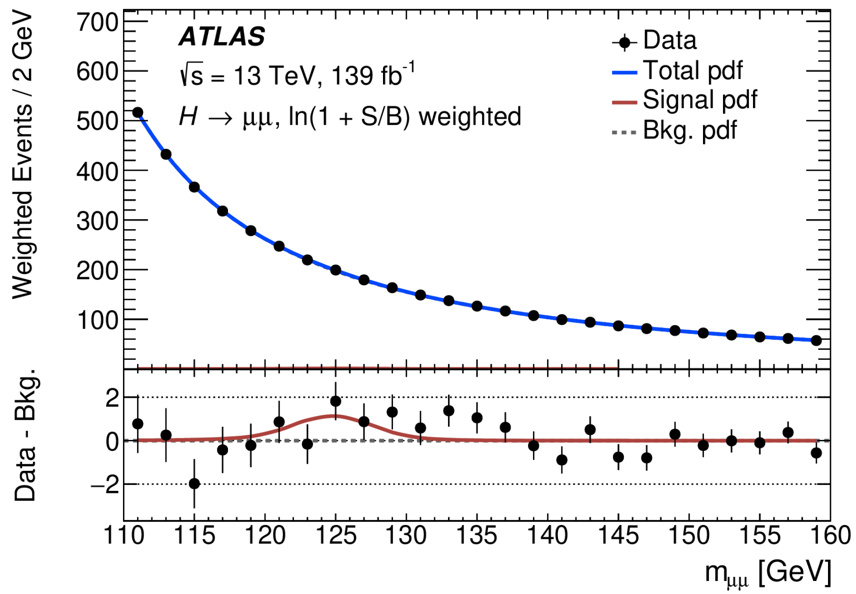
H→cc:

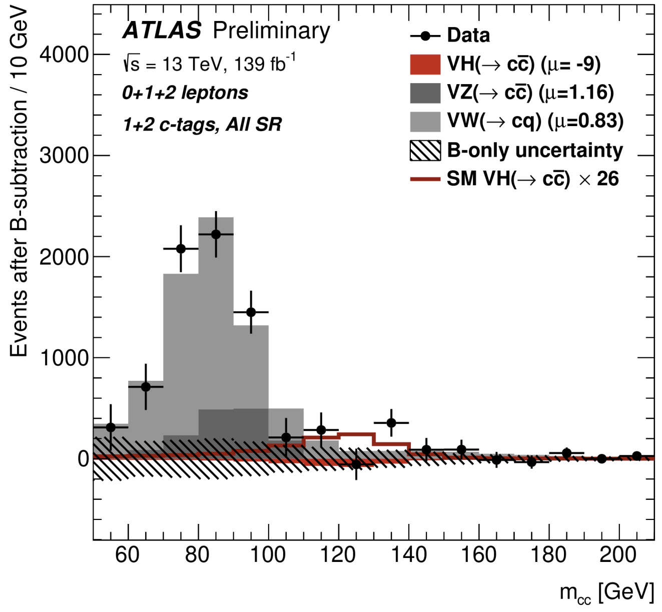
- Observed limit of 26 x SM on VH(cc) (for 31 x SM expected)
- First direct limit on κ_c @ 95%CL with $|\kappa_c| < 8.5$

Indirect constraints:

- $H\to\gamma\gamma$, p_T^H shape-only: $-19 < \kappa_c < 26$
- $H\to ZZ^* \to 4l$, p_T^H shape-only: $-11.7 < \kappa_c < 10.5$
- $H\to ZZ^* \to 4l$, p_T^H shape & norm: $-7.5 < \kappa_c < 9.4$

→ Great results with Run 2 and lots to look forward to in Run 3 and at HL-LHC!





Thank you!

Any questions?

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 selection / modelling uncertainities

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
ΔR(jet 1, 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)
$\min \lvert\Delta\phi(E_T^{miss}, \text{jet})\rvert$	$> 20°$ (2 jets) , $> 30°$ (3 jets)
$\lvert\Delta\phi(E_T^{miss}, H)\rvert$	$> 120°$
$\lvert\Delta\phi(\text{jet1}, \text{jet2})\rvert$	$< 140°$
$\lvert\Delta\phi(E_T^{miss}, p_T^{miss})\rvert$	$< 90°$
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

$VH(\rightarrow b\bar{b})$	
$WH(\rightarrow b\bar{b})$ normalisation	27%
$ZH(\rightarrow b\bar{b})$ normalisation	25%
Diboson	
$WW/ZZ/WZ$ acceptance	10/5/12%
p_T^V acceptance	4%
N_{jet} acceptance	7 – 11%
Z+jets	
$Z+hf$ normalisation	Floating
$Z+mf$ normalisation	Floating
$Z+lf$ normalisation	Floating
$Z+bb$ to $Z+cc$ ratio	20%
$Z+bl$ to $Z+cl$ ratio	18%
$Z+bc$ to $Z+cl$ ratio	6%
p_T^V acceptance	1 – 8%
N_{jet} acceptance	10 – 37%
High ΔR CR to SR	12 – 37%
0- to 2-lepton ratio	4 – 5%
W+jets	
$W+hf$ normalisation	Floating
$W+mf$ normalisation	Floating
$W+lf$ normalisation	Floating
$W+bb$ to $W+cc$ ratio	4 – 10 %
$W+bl$ to $W+cl$ ratio	31 – 32 %
$W+bc$ to $W+cl$ ratio	31 – 33 %
$W \rightarrow \tau\nu(+c)$ to $W+cl$ ratio	11%
$W \rightarrow \tau\nu(+b)$ to $W+cl$ ratio	27%
$W \rightarrow \tau\nu(+l)$ to $W+l$ ratio	8%
N_{jet} acceptance	8 – 14%
High ΔR CR to SR	15 – 29%
$W \rightarrow \tau\nu$ SR to high ΔR CR ratio	5 – 18%
0- to 1-lepton ratio	1 – 6 %
Top quark (0- and 1-lepton)	
top(b) normalisation	Floating
top(other) normalisation	Floating
N_{jet} acceptance	7 – 9%
0- to 1-lepton ratio	4%
SR/top CR acceptance ($t\bar{t}$)	9%
SR/top CR acceptance (Wt)	16%
Wt / $t\bar{t}$ ratio	10%
Top quark (2-lepton)	
Normalisation	Floating
Multi-jet (1-lepton)	
Normalisation	20 – 100%

Breakdown of uncertainties

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
Systematics		11.5	0.21	0.36
Statistical uncertainties				
Data statistics only		7.8	0.05	0.23
Floating 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 statistics		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

Signal regions

Discriminant: m_{cc} of the two leading p_T jets

Signal:

VH(cc), VZ(cc), VW(cq)

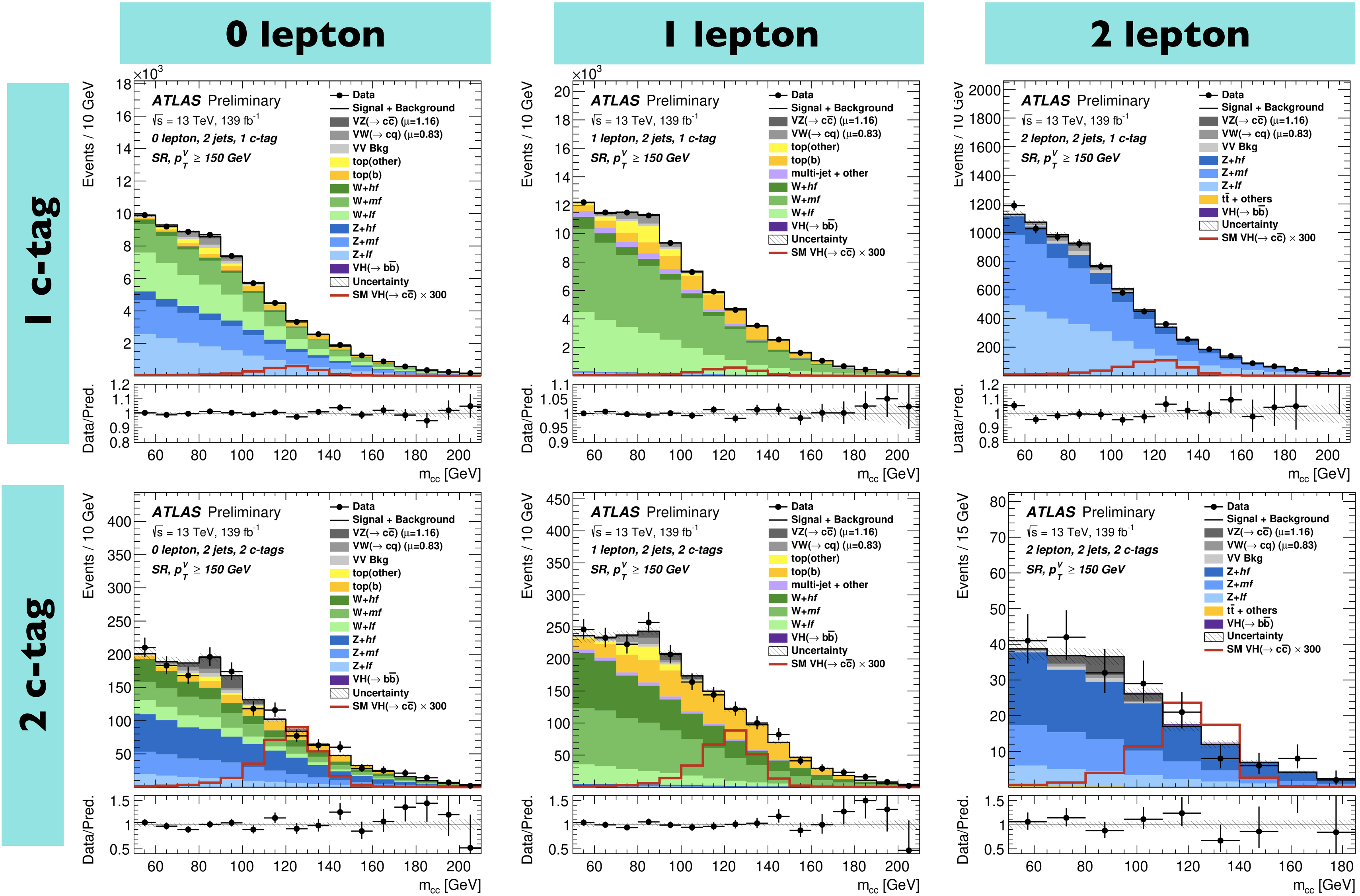
Major backgrounds:

W+jets, Z+jets, Top

→ Constrained in dedicated control regions

Subdominant backgrounds:

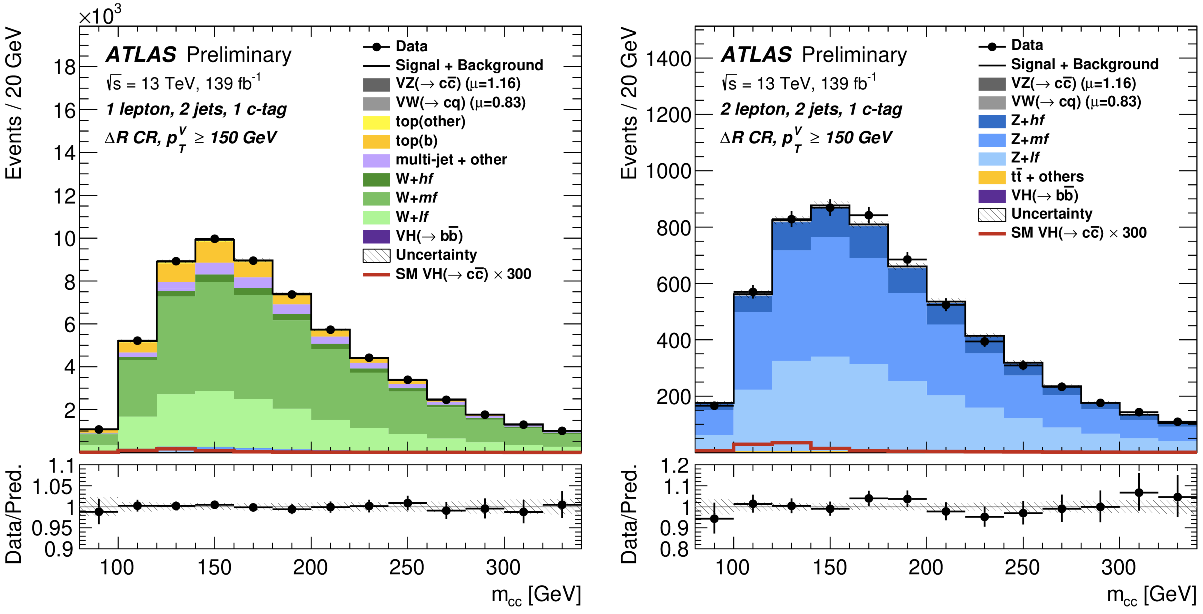
VH(bb), VV background



V+jets background

- V+jets (split as W and Z+jets) split into flavours:
  - **V+hf:** V+cc, V+bb
  - **V+mf:** V+bc, V+bl, V+cl
  - **V+l**
- All V+jets normalisations floating in fit
- V+hf and V+mf floating normalisations determined with the help of a **high ΔR_{cc} control region**
- One ΔR_{cc} CR for each corresponding SR:
  - Low pTV: $2.3 < \Delta R_{cc} < 2.5$
  - Medium pTV: $1.6 < \Delta R_{cc} < 2.5$
  - High pTV: $1.2 < \Delta R_{cc} < 2.5$
- V+l floating normalisations determined **in 0 c-tag CR** and 1 and 2 lepton

High ΔR_{cc} control region



Top background

- Top background: ttbar and single top
- Define **top control region in 0 and 1 lepton** channel by inverting b-veto on the 3rd jet
- Combine ttbar and Wt into floating normalisations split by flavour:
  - **Top(bq):** ttbar+Wt with dijet flavour bc, bl, bτ
    → non-resonant
  - **Top(lq):** ttbar+Wt with dijet flavour cl, l
    → resonant
- **Top CR in 2 lepton** → minor background, single-bin CR, with normalisation only

TopCR in 0 and 1 lepton