Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment

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on behalf of the ATLAS Collaboration

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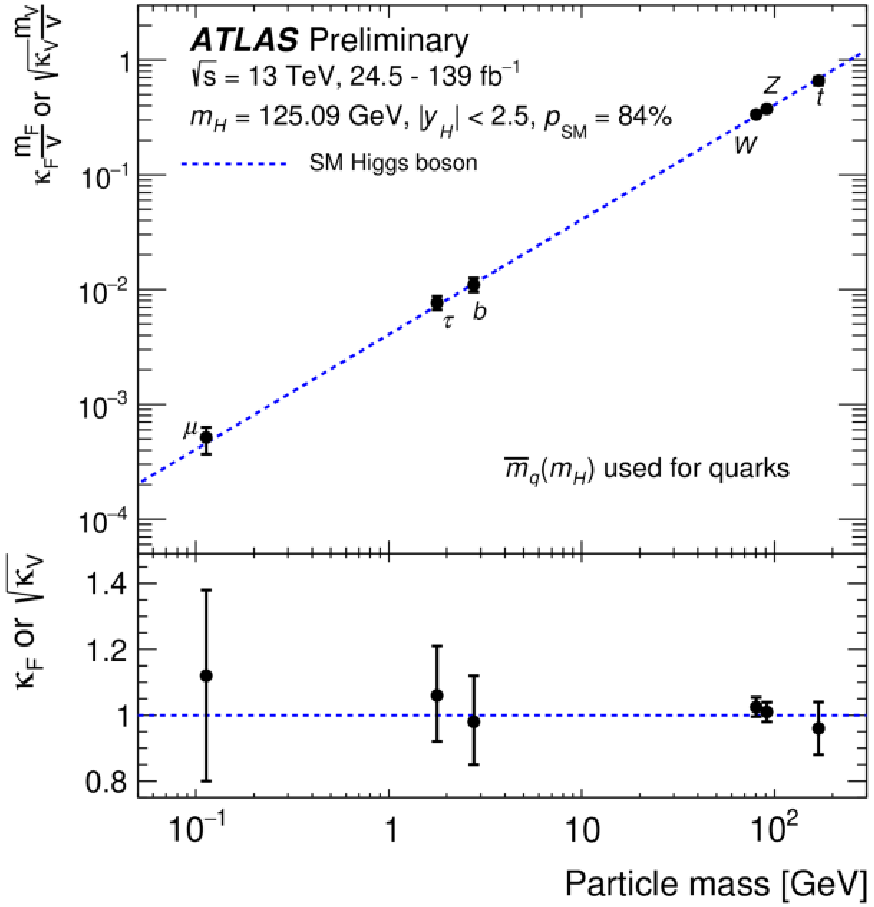
ATLAS EXPERIMENT

SLAC NATIONAL ACCELERATOR LABORATORY

Why search for H->cc

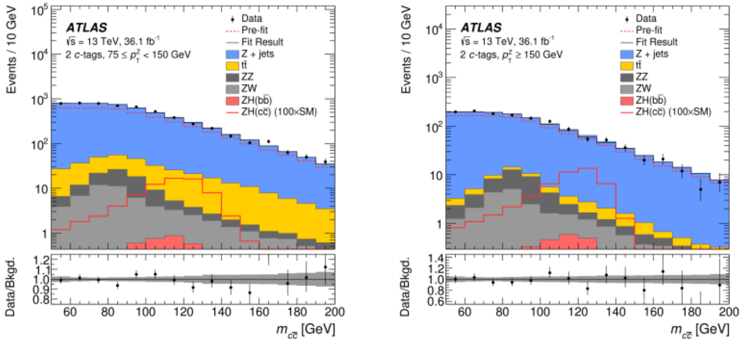
- Standard Model Higgs boson discovered in 2012!
- The measurements at LHC have established Higgs Yukawa couplings to Fermions are close to the Standard Model(SM) expectation for the 3rd Fermion generation
  - H->bb, H->ττ, ttH
- universal Yukawa coupling for other Fermion generations has a little experimental constraint
  - evidence of H-> μμ, JHEP 01 (2021) 148
- The search of H->cc decay is crucial for directly probing the Higgs mechanism for the 2nd generation of fermions/quarks



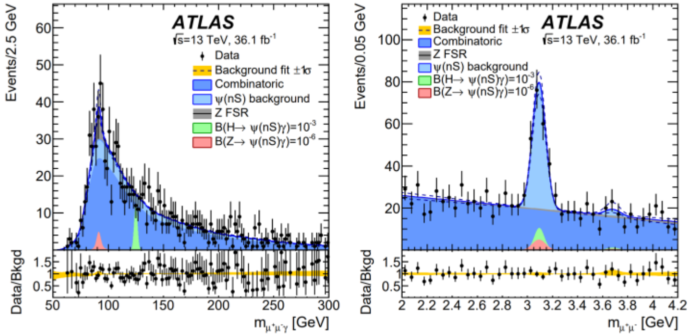
https://atlas.cern/updates/briefing/higgs-boson-finds-strength-unity

Previous ATLAS/CMS Direct Search Results

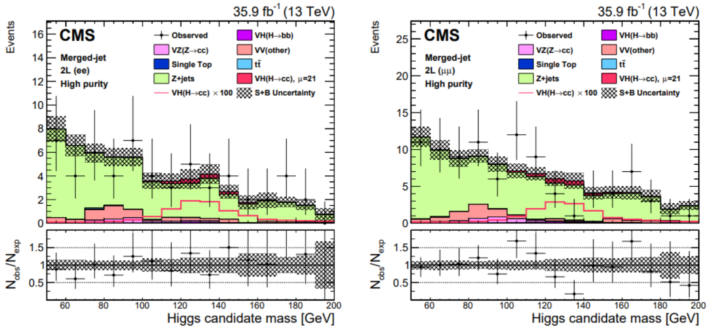
- ATLAS, PRL 120 (2018) 211802
  - Z(ll)H only, 36/fb
  - obs 110xSM (exp 150 +80 -40)



- ATLAS, PLB 786 (2018) 134
  - H->J/ψγ, 36/fb
  - obs 116xSM (exp 100 +47 -27)

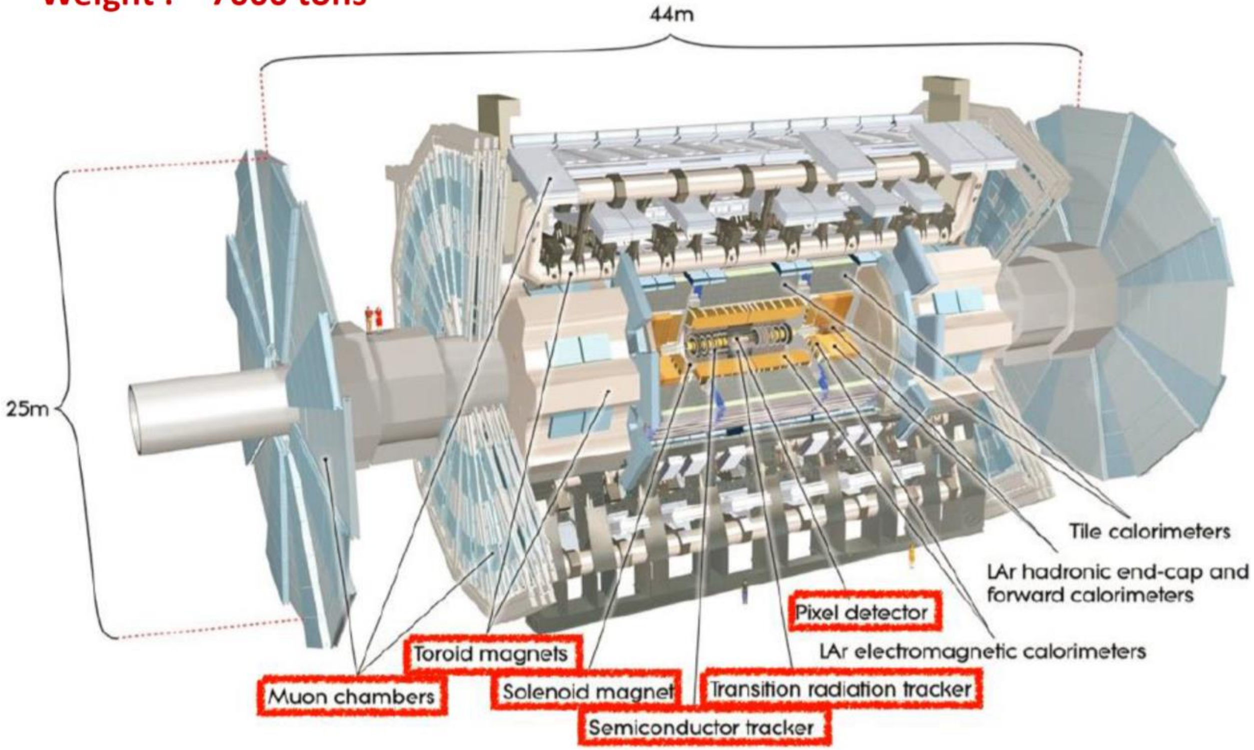


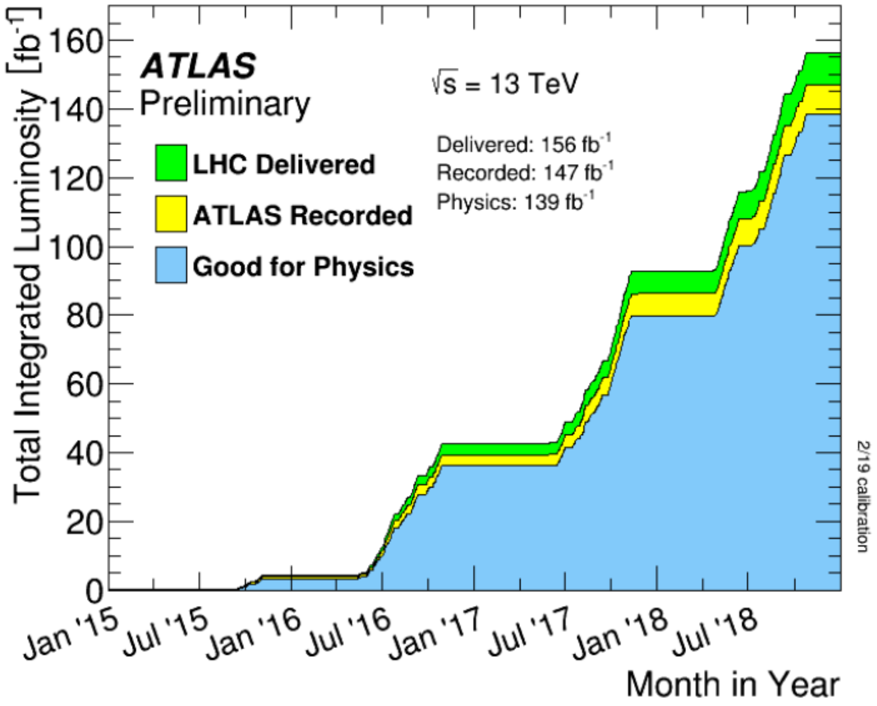
- CMS, JHEP 03 (2020) 131
  - Z(vv)H, W(lv)H, Z(ll)H. 36/fb
  - obs 70xSM (exp 37 +16 -10)



ATLAS Detector and Run-2 Data-taking

Weight : ~ 7000 tons

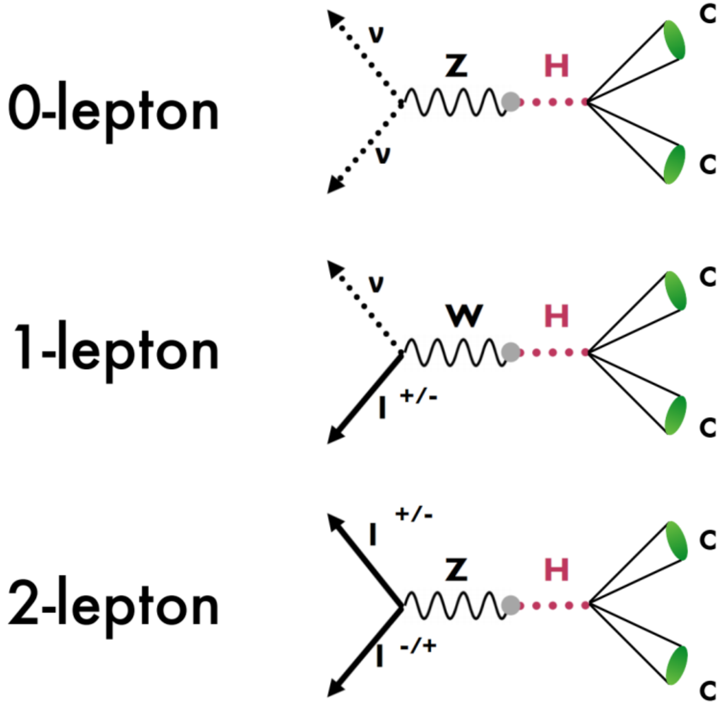




21.0×10^{33} cm^{-2} s^{-1}

ATLAS full run2 H->cc search

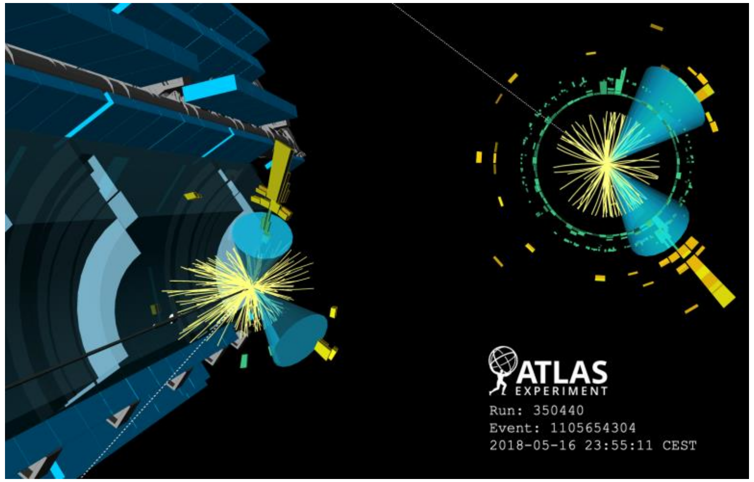
- Full Run2 Dataset, 139 fb-1
- Looking for Higgs bosons produced together with a vector boson (W/Z) to moderate the contamination from huge QCD background
  - events are separated by number of leptons
  - targeting ZH->vvcc, WH->lvcc, ZH->llcc
- Diboson processes, VW(cq) and VZ(cc), are used to validate the analysis strategy
- Multivariate flavor tagging algorithms are used to distinguish jets originating from the hadronization of charm quarks, bottom quarks, or light-quarks/gluons



ATLAS full run2 VHcc search

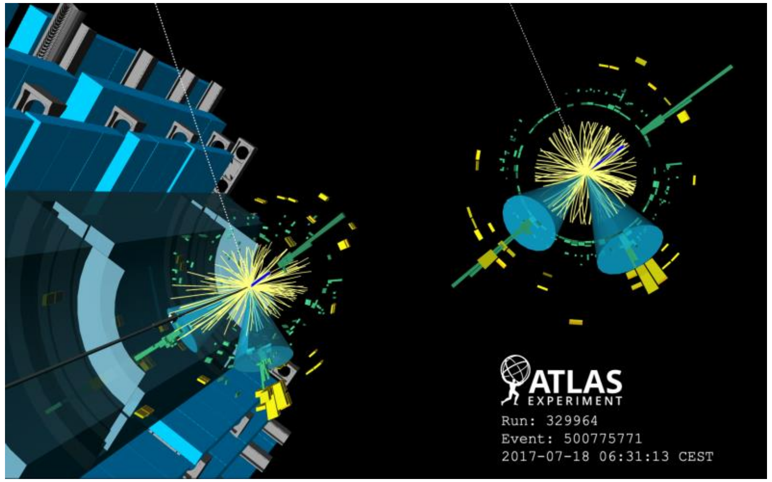
0Lep

- 2 c-tagged jets (blue cones)
- large missing transverse energy (dash-line)



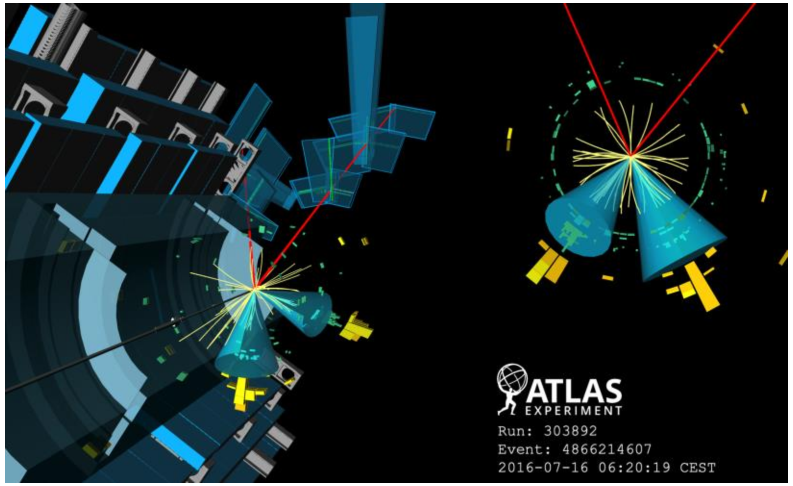
1Lep

- 2 c-tagged jets (blue cones)
- 1 electron (green)
- large missing transverse energy (dash-line)



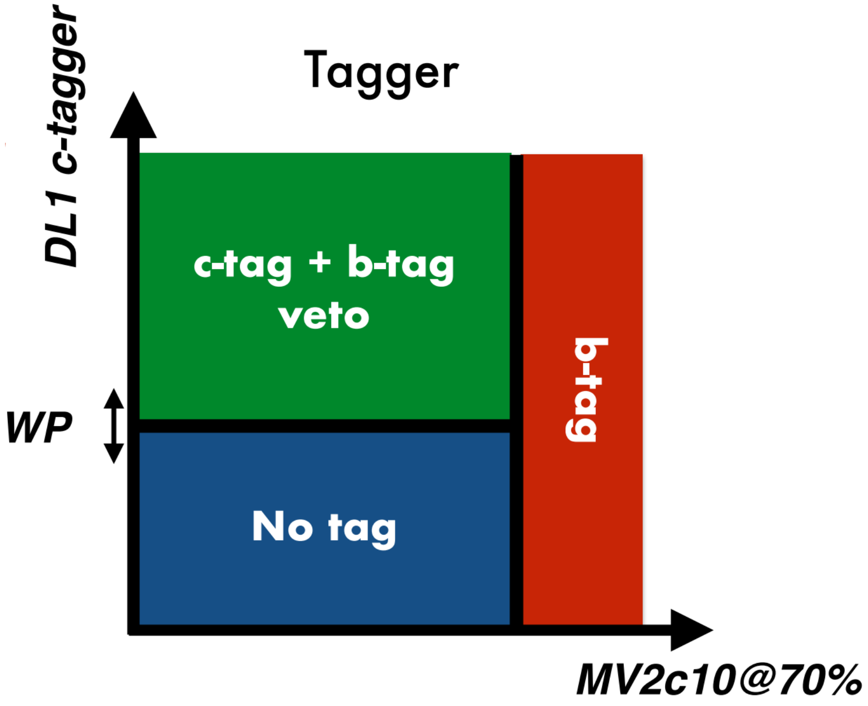
2Lep

- 2 c-tagged jets (blue cones)
- 2 muons (red line)



Object Selection

- Muon and electron
  - 2Lep channel: $81<m(ll)<101$ GeV
  - diff. rate of fake lepton, 1Lep and 2Lep channels use diff. selection criteria
- Jet: anti-kt algorithm with radius parameter R=0.4
  - the two leading jets must be in detector central region for flavor tagging (b-veto && c-tag)
  - b-veto for rest of jets
- Missing transverse momentum
  - negative of the vector sum of the pT of jets, electrons, muons, hadronically-decaying tau, and “soft term”
- Additional cuts are applied to reduce backgrounds or define control-regions



Performance

	c-tagging efficiency
c-jets	27%
b-jets	8%
light-jets	1.6%

ΔR_{cc} cuts		
	75 GeV p_{TV} < 150 GeV	ΔR_{cc} cut = 2.3
	150 GeV < p_{TV} < 250 GeV	ΔR_{cc} cut = 1.6
	p_{TV} > 250 GeV	ΔR_{cc} cut = 1.2

Event Categorization

- 0/1Lep: num(jets)<4, in order to reduce top backgrounds
- low pTV(75-150) is used in 2Lep channel, because of less QCD contamination

		$\Delta R_{cc} < \Delta R_{cc}$ cut				ΔR_{cc} cut < ΔR_{cc} < 2.5	
		0tag CR	SR		Top CR	ΔR_{cc} CR	
0 L	pTV > 150 GeV		1tag 2jet	2tag 2jet		1tag 2jet	2tag 2jet
0 L	pTV > 150 GeV		1tag 3jet	2tag 3jet	1 tag 3 jet	1tag 3jet	2tag 3jet
1 L	pTV > 150 GeV	0tag 2jet	1tag 2jet	2tag 2jet		1tag 2jet	2tag 2jet
1 L	pTV > 150 GeV	0tag 3jet	1tag 3jet	2tag 3jet	1 tag 3 jet	1tag 3jet	2tag 3jet
2 L	Low pTV	0tag 2 jet	1tag 2jet	2tag 2jet	1tag 2 jet	1tag 2jet	2tag 2jet
2 L	Low pTV	0tag 3+jet	1tag 3+jet	2tag 3+jet	1tag 3+jet	1tag 3+jet	2tag 3+jet
2 L	pTV > 150 GeV	0tag 2 jet	1tag 2jet	2tag 2jet	1tag 2 jet	1tag 2jet	2tag 2jet
2 L	pTV > 150 GeV	0tag 3+jet	1tag 3+jet	2tag 3+jet	1tag 3+jet	1tag 3+jet	2tag 3+jet

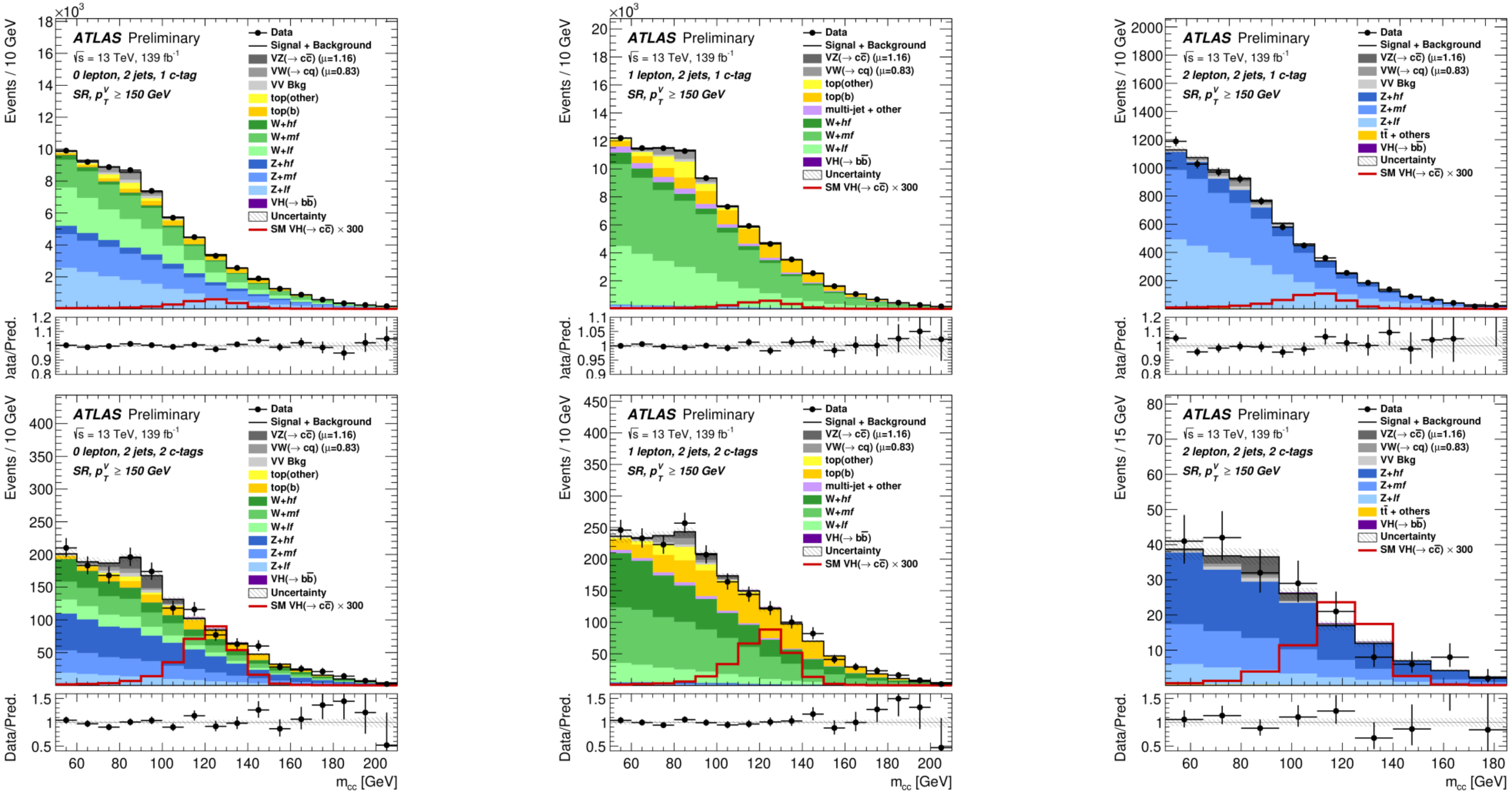
Legend

- Binned SR
- Binned CR
- One-bin CR

16 SRs
+ 28 CRs
= 44 regions

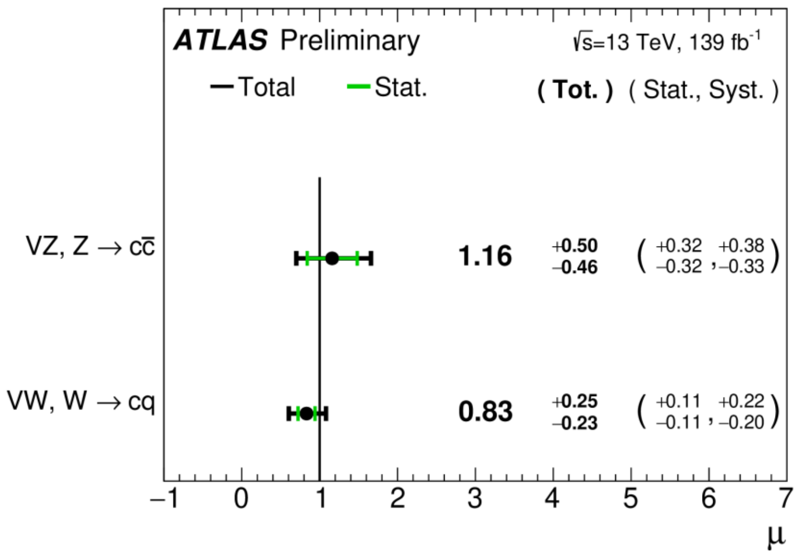
Post-fit m(cc) distributions for 6 selected SRs

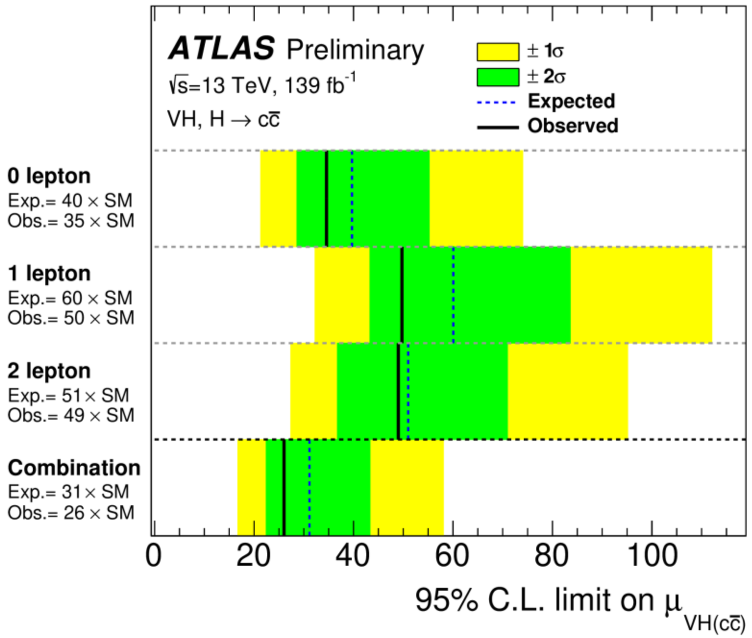
- Binned profile likelihood fit on m(cc) distribution simultaneously in 16 SRs and 28 CRs

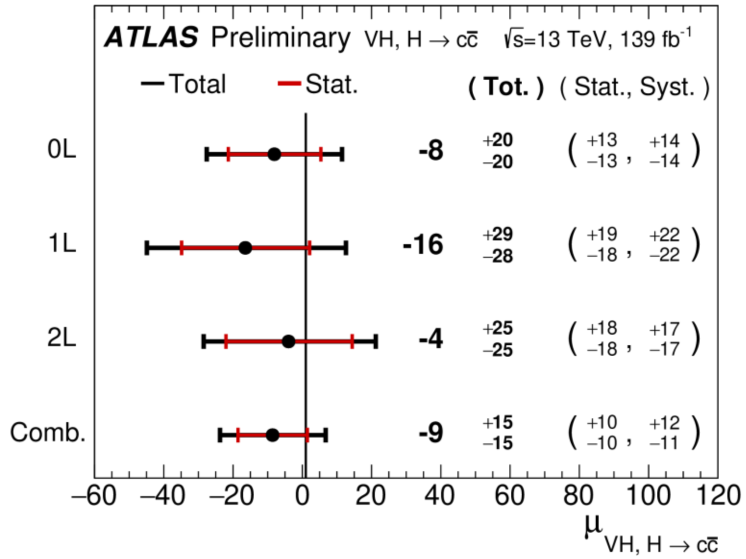


Results

- SM VZ(cc) signal significance: **2.6** σ
- SM VW(cq) signal significance: **3.8** σ
- **world's tightest direct constraint on H->cc**
  - W/ZH(cc) **obs**(exp) < **26** (31) xSM

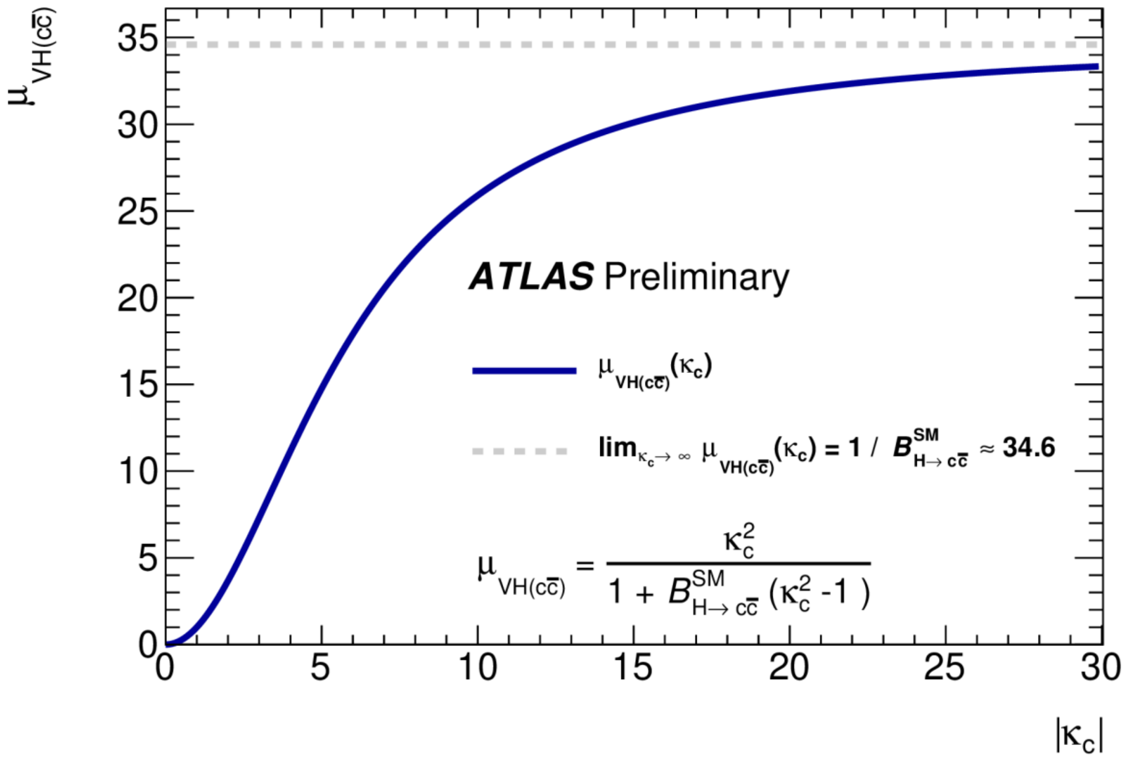


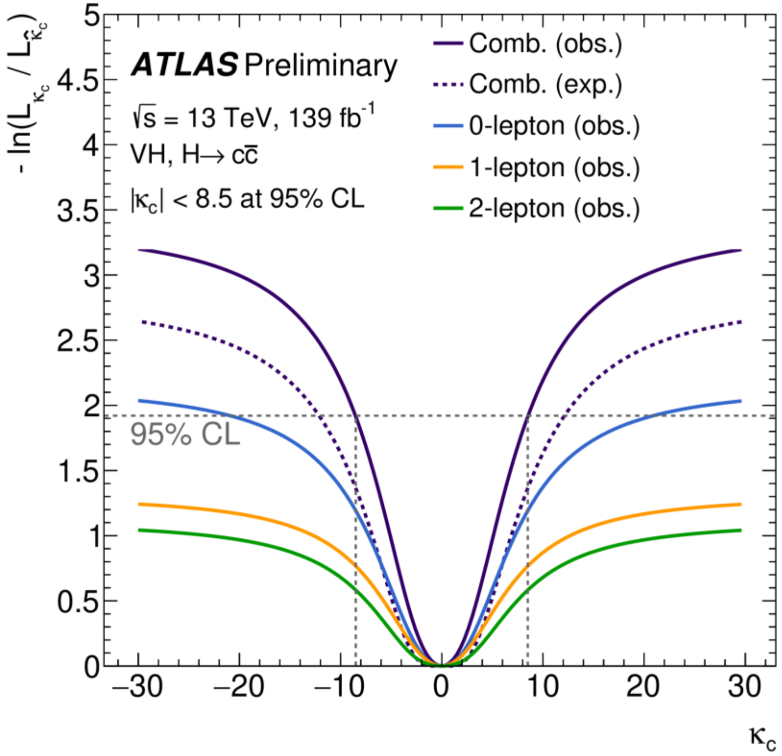




κ_c interpretation

- κ_c: quantify possible deviations from the SM
  - signal strength as a function of coupling enhancement Kc
  - Assuming κ=1 for other fermions and bosons and no BSM contributions to Higgs width





Backup

Signal and bkg MC

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 [49, 50] + GoSam [59] + MiNLO [60, 61]	NNPDF3.0NLO [51]	Pythia 8.212 [52]	AZNLO [53]	NNLO(QCD) +NLO(EW) [54–58]
$gg \to ZH$ $(H \to c\bar{c}/b\bar{b})$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NLO+NLL [62, 63]
$t\bar{t}$	Powheg-Box v2 [64]	NNPDF3.0NLO	Pythia 8.230	A14 [65]	NNLO +NNLL [66–72]
t/s-channel single top	Powheg-Box v2 [73]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [74, 75]
Wt-channel single top	Powheg-Box v2 [76]	NNPDF3.0NLO	Pythia 8.230	A14	Approx. NNLO [77, 78]
V+jets	Sherpa 2.2.1 [46–48]	NNPDF3.0NNLO [51]	Sherpa 2.2.1	Default	NNLO [79]
$qq \to VV$	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

Signal region 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
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

bkg modelling systematic uncertainties

$VH(\to b\bar{b})$	
$WH(\to b\bar{b})$ normalisation	27%
$ZH(\to b\bar{b})$ 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 %
$W \to \tau\nu(+c)$ to $W + cl$ ratio	11%
$W \to \tau\nu(+b)$ to $W + cl$ ratio	27%
$W \to \tau\nu(+l)$ to $W + l$ ratio	8%
N_{jet} acceptance	8 – 14%
High ΔR CR to SR	15 – 29%
$W \to \tau\nu$ 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%

signal strength 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
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
$E_{\mathrm{T}}^{\mathrm{miss}}$		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