Measurements of Higgs boson production using decays to two c-quarks with the ATLAS detector

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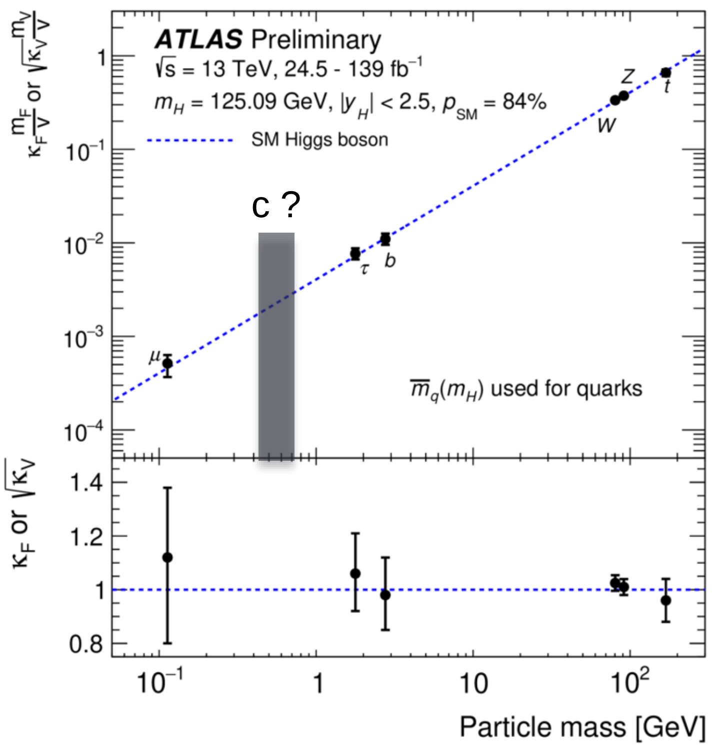
Higgs potential and BSM opportunity, Aug 27-31, 2021

Motivation for H➔cc

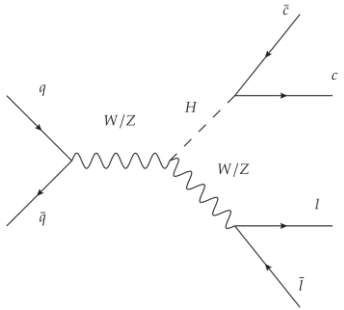


- Coupling between Higgs boson and all 3rd generation quarks has been measured.
- For the 2nd generation quarks, the Yukawa coupling is still not measured, yet not confirmed.
- In the rest coupling constants to be measured, Y_c(*) is the largest.
- H➔cc is the most direct channel to measure κ_c.
  - κ_c can be modified in BSM models (2HDM, HVT, ...)

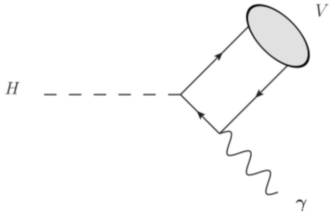
(*) Charm quark Yukawa coupling constant

Previous H→cc search results

VH→cc



H→J/ψ + γ



- Phys. Rev. Lett. 120 (2018) 211802
  - Previous ATLAS Z(l+l-)Hcc result with 36.1 fb^{-1} $\sqrt{s} = 13$ TeV data
  - Observed (expected) limit of μ_{ZHcc} is **110 (150^{+80}_{-40})**
- JHEP 03 (2020) 131
  - Previous CMS VHcc result with 35.9 fb^{-1} $\sqrt{s} = 13$ TeV data
  - Using 3 channels: W→lv, Z→ll, Z →vv
  - Both resolved and boosted (2 charm jets merged into one fat jet due to large boost) regions are used
  - Observed (expected) limit of μ_{VHcc} is **70 $(37^{+15.4}_{-10.8})$**

- $\mathrm{H} \rightarrow \mathrm{J}/\psi + \gamma, \mathrm{J}/\psi \rightarrow \mu^{+}\mu^{-}$, 36 fb^{-1} Run 2, ATLAS **125x SM** *Phys. Lett. B 786 (2018) 134*, CMS **642x SM** *Phys. Lett. B 797 (2019) 134811*

1 lepton candidate event W(eν)H(cc)

$\Delta\phi = -1.37$

$m_{CC} = 124.29$ GeV

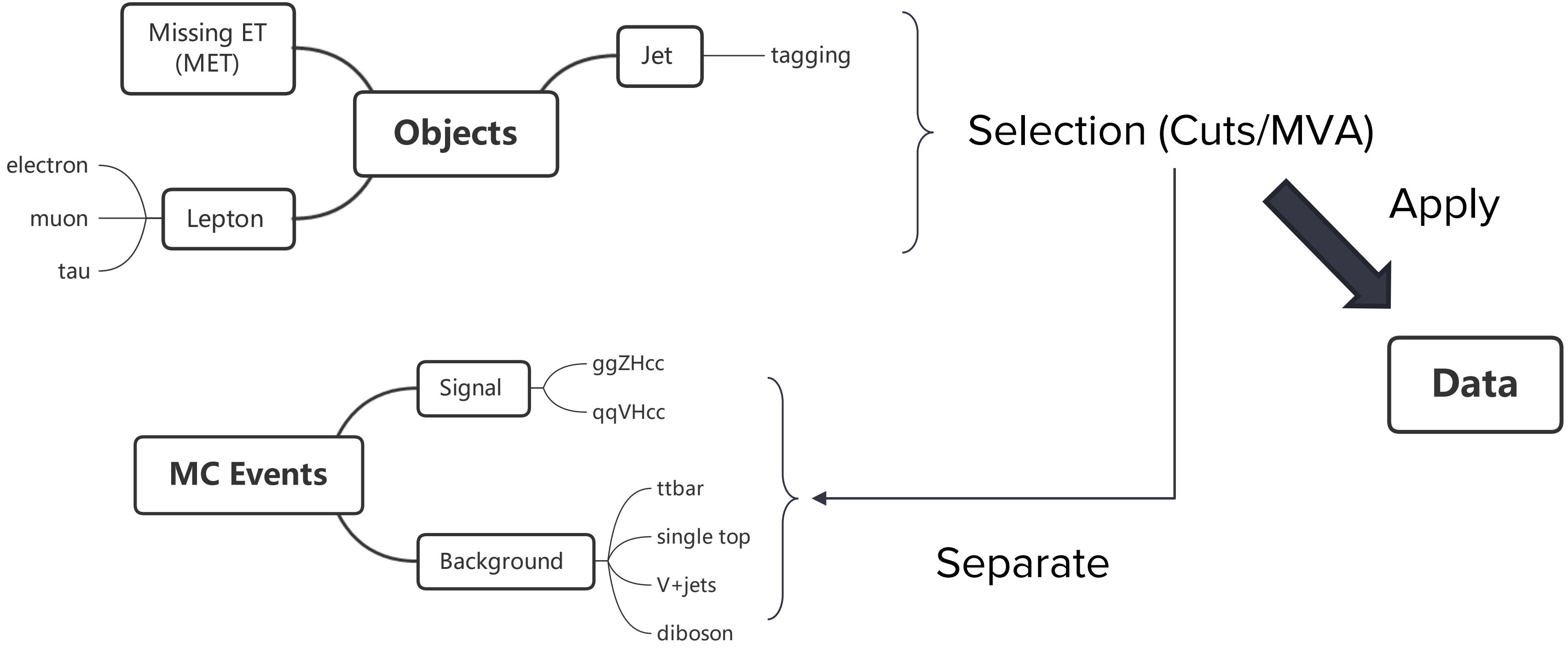
$p_{TJ1} = 111.6$ GeV

$p_{TJ2} = 81.27$ GeV

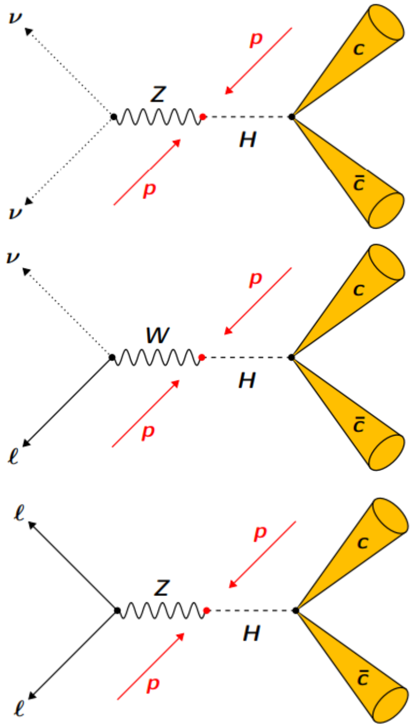
$\eta_{J1} = 0.83$

$\eta_{J2} = 0.52$

VH(H→cc) analysis syllables



VH(H→cc) search strategy



0 lepton

1 lepton

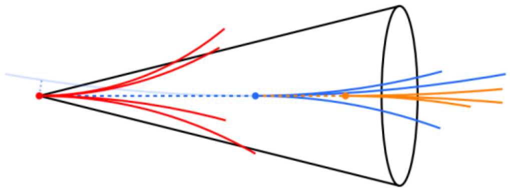
2 lepton

- Use 139 fb^{-1} full Run 2 data recorded by ATLAS
- **Cut-based analysis**: final discriminant is m_{cc}
- 1 and 2 c-tag (defined using tagging algorithms) categories and several pTV and nJet bins:

	1 c-tag		2 c-tag	
$75 < p_T^V < 150$ GeV (*)	2 jet	3(+) jet	2 jet	3(+) jet
$p_T^V > 150$ GeV	2 jet	3(+) jet	2 jet	3(+) jet

pTV – transverse momentum of the vector boson
(*) only in 2 lepton channel

Tagging



MVA tagger
(DL1, MV2c10, etc)

- b-jet
- c-jet
- light-jet

- Combined tagger: c-tagging + b-veto:
  - **DL1** as a c-tagger
  - b-veto using **MV2c10** 70% WP
- Dedicated optimization of WP:
  - c-jets (27%), b-jets (8.3%), light-jets (1.7%)

VH(cc) SR

Sub-leading jet \ Leading jet	!c!b	c!b	b
b	0 c-tag	1 c-tag	0 c-tag
c!b	1 c-tag	2 c-tag	1 c-tag
!c!b	0 c-tag	1 c-tag	0 c-tag

- 1-ctag
- 2-ctag

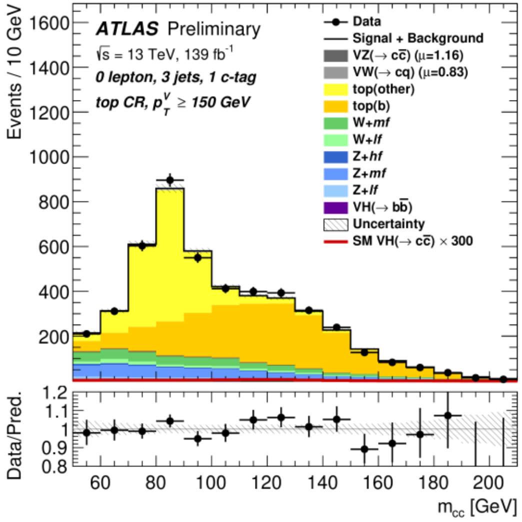
Event selection

- Region-specific selections
- Common selections

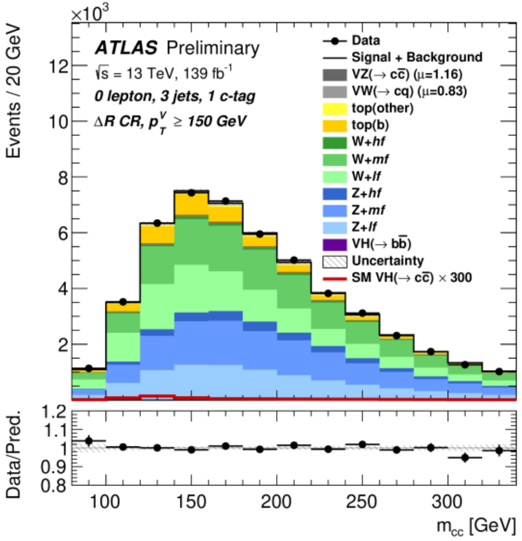
Common Selections	
Central jets	≥ 2
Signal jet p_T	≥ 1 signal jet with $p_T > 45$ GeV
c-jets	1 or 2 c-tagged signal jets
b-jets	No b-tagged non-signal jets
Jets	2, 3 (0- and 1-lepton), 2, ≥ 3 (2-lepton)
p_T^V regions	75–150 GeV (2-lepton) > 150 GeV
ΔR(jet 1, jet 2)	$75 < p_T^V < 150$ GeV: $\Delta R \leq 2.3$ $150 < p_T^V < 250$ 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

Background Control Regions



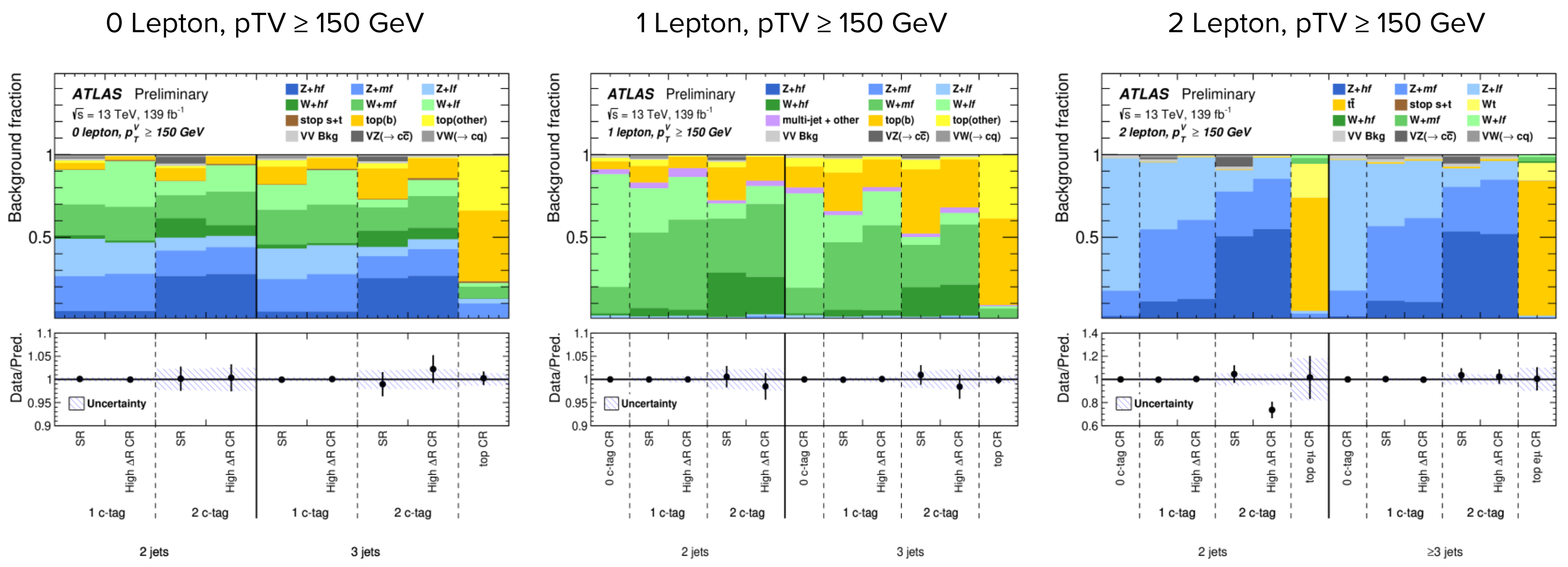
top control region



High ΔR control region

- 0 c-tag control region
  - None of the two leading jets is c-tagged
- Top control region
  - The third jet is b-tagged
  - Only for 1 c-tag
- Top eμ control region
  - One bin, only for 2 lepton region
- High ΔR control region
  - Inverse the ΔR cut

Background composition



Z+jets (0L, 2L), W+jets (0L, 1L) and top backgrounds (0L, 1L) are the major backgrounds

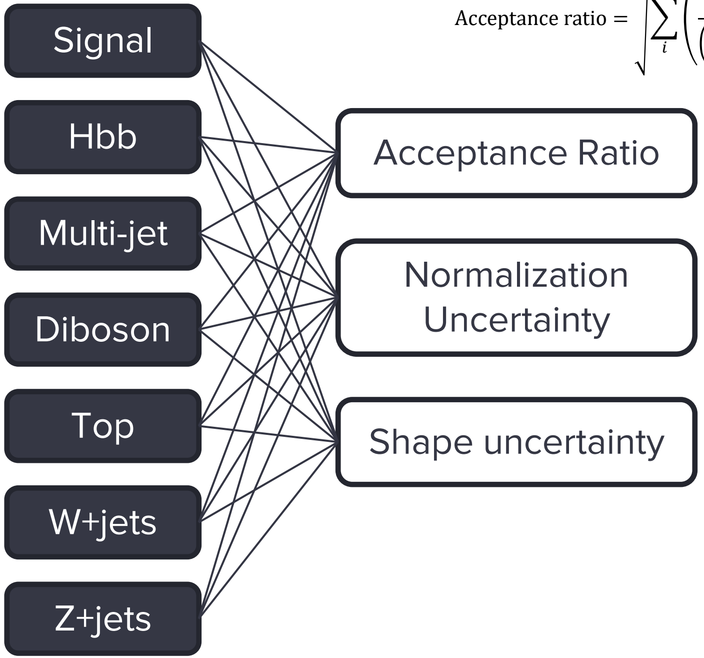
Uncertainties

Experimental uncertainties:

- Luminosity and Pile-up Simulation
- Lepton triggers
- MET trigger
- Lepton and MET Reconstruction
- Jet Energy Scale and Resolution
- Flavour Tagging
- Truth Tagging

Modelling uncertainties:

$$\text{Acceptance ratio} = \sqrt{\sum_i \left(\frac{\left(\frac{n_1}{n_2}\right)_i}{\left(\frac{n_1}{n_2}\right)_{\text{nominal}}} - 1 \right)^2}$$



Derived using different generators across different regions

Derived using different scales (muR, muF) and PDF sets

Simultaneous profile likelihood binned fit to all regions

Signal strength

Systematic uncertainty

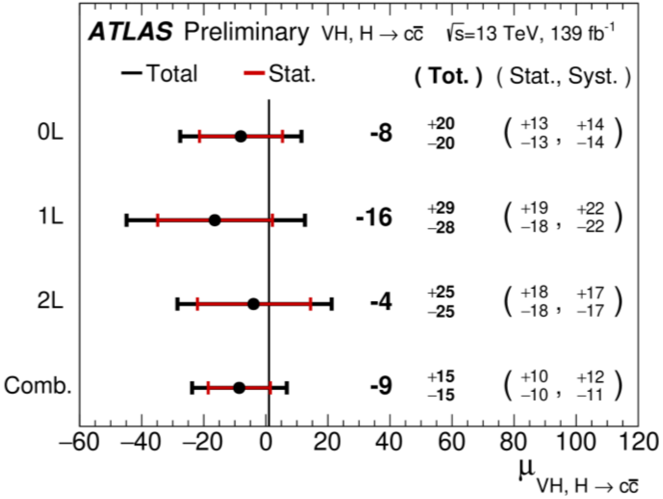
MC statistical uncertainty

$$\mathcal{L}(\mu,\vec{\theta},\vec{\gamma}\,) = \underbrace{\prod_{i\in\text{bins}}}_{\text{bins in all signal regions}} \text{Pois}\left(N_i \middle| \boldsymbol{\mu} s_i(\vec{\theta}) + \boldsymbol{\gamma_i} b_i(\vec{\theta})\right) \times \prod_{\theta\in\vec{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \times \prod_{i\in\text{bins}} \text{Gauss}(\beta_i|\gamma_i\beta_i,\sqrt{\gamma_i\beta_i})$$

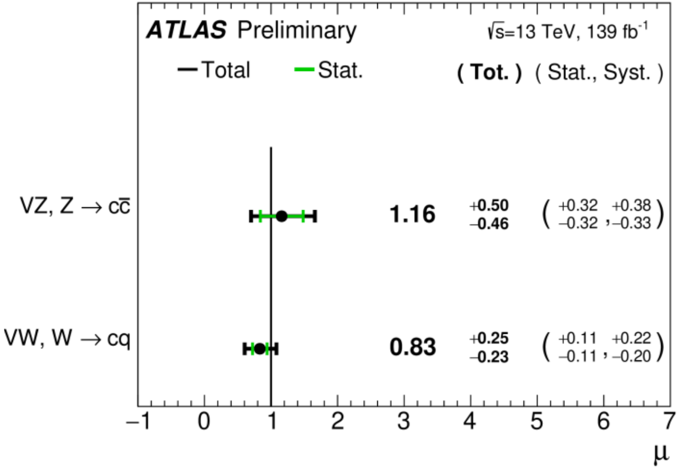
- Control regions are not shown
- 3 parameters of interest (POIs): $\mu_{VH(cc)}$, $\mu_{VZ(cc)}$, $\mu_{VW(cq)}$
- The free-floating normalization factors are not listed in the formula:
  - top background which decay into one **b quark** and one other quark (or tau lepton) (bc, bl, bb, bτ)
  - top background which decay into one **c quark or light flavor quark** and one other quark (cl, l, cc)
  - ttbar (2L)
  - Wmf, Zmf (bc, bl, cl and W(τν)+b, W(τν)+c in 0L)
  - Whf, Zhf (cc, bb)
  - Wl, Zl (W(τν)+l in 0L)

Best-fit Results

- Signal strengths from the 3 POI fit:
    - VH(cc): -8.58 +/- 15.14
    - VW(cl): 0.83 +/- 0.24
    - VZ(cc): 1.16 +/- 0.48
- All signal strengths in agreement with SM within 1σ
- Compatibility with SM (μ=1): 84%



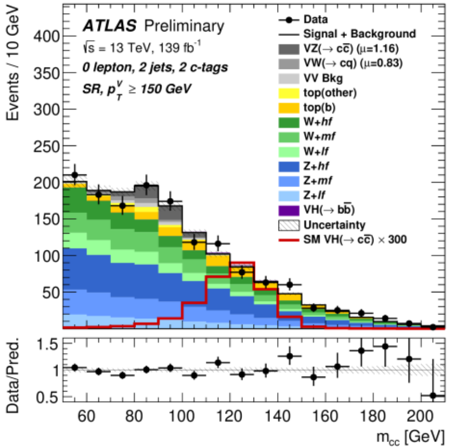
H(cc) in combined fit and decorrelated across channels



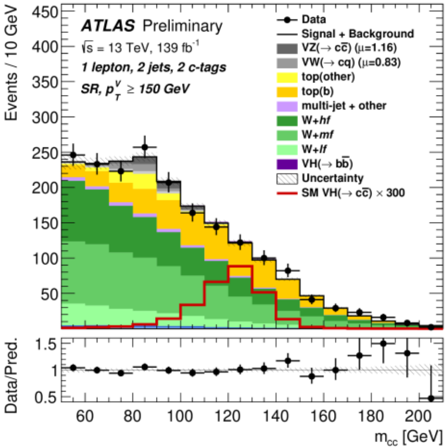
Diboson POIs in 3 POI fit

Post-fit plots and normalization factors

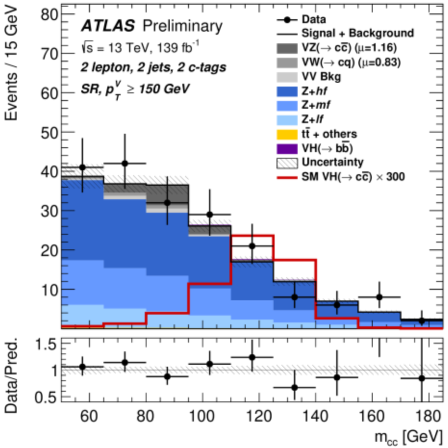
0 Lepton, pTV ≥ 150 GeV



1 Lepton, pTV ≥ 150 GeV



2 Lepton, pTV ≥ 150 GeV



Background	p_T^V	Jets	Value
top(b)			0.91 ± 0.06
top(other)			0.94 ± 0.08
$t\bar{t}$ (2 lep)	$p_T^V > 150$ GeV	2	0.76 ± 0.22
		3	0.96 ± 0.13
	$75 < p_T^V < 150$ GeV	2	1.08 ± 0.08
		3	1.06 ± 0.07
$W+hf$			1.16 ± 0.35
$W+mf$			1.28 ± 0.14
$W+lf$		2	1.02 ± 0.04
		3	0.97 ± 0.05
$Z+hf$	$p_T^V > 150$ GeV		1.19 ± 0.22
	$75 < p_T^V < 150$ GeV		1.25 ± 0.25
$Z+mf$	$p_T^V > 150$ GeV		1.10 ± 0.15
	$75 < p_T^V < 150$ GeV		1.11 ± 0.15
$Z+lf$	$p_T^V > 150$ GeV	2	1.07 ± 0.03
		3	1.08 ± 0.05
	$75 < p_T^V < 150$ GeV	2	1.12 ± 0.04
		3	1.07 ± 0.06

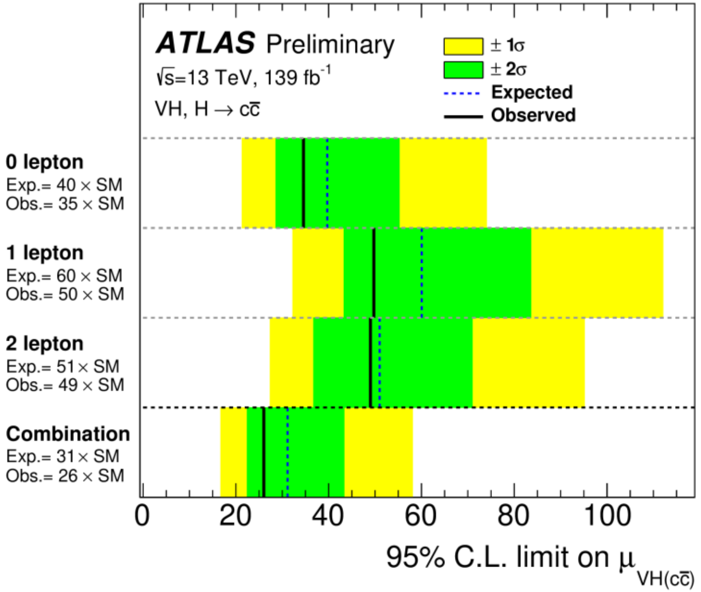
Limits and significances

- Observed VH(cc) limit of **26 x SM** (31 x SM expected)
  - Highest sensitivity in 0 lepton channel
- Diboson
  - VW(cl) significance of **3.84 σ** (4.60 σ expected)
  - VZ(cc) significance of **2.61 σ** (2.24 σ expected)
- Uncertainties
  - Dominated by statistics
  - As for systematic uncertainty, modelling uncertainty for Z+jets is dominant

	Expected	Observed
VH(cc) limit	$31.1^{+12.2}_{-8.7}$	26.0

VW(cl) significance	4.60 σ	3.84 σ
VZ(cc) significance	2.24 σ	2.61 σ

First in ATLAS



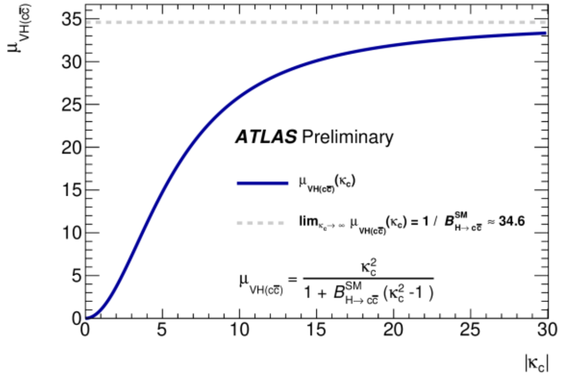
Expected and observed limit in combined fit and with POI decorrelated into channels

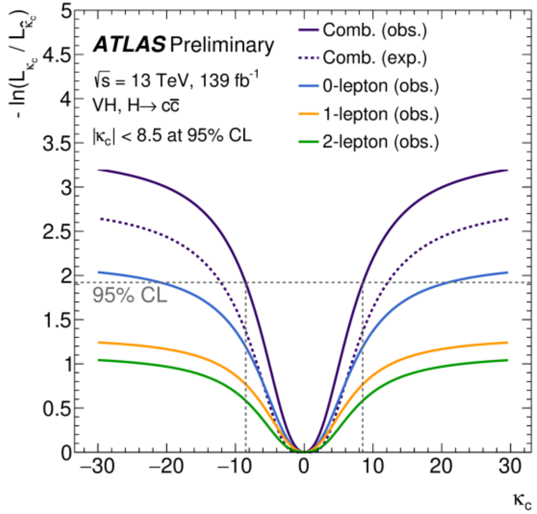
κ_c interpretation

- $\mu(\kappa_c) = \dfrac{\kappa_c^2}{B(H\to c\bar{c})\kappa_c^2 + \left(1 - B(H\to c\bar{c})\right)}$

  (other coupling modifiers set to 1)
- Expected limit on κ_c at 95% CL in combined fit $|\kappa_c| < 12.4$
- Observed best fit $\kappa_c = 0$
- Current best limit on κ_c @ 95%CL with $|\kappa_c| < 8.5$

Combined fit	**68% CL**	**95% CL**
Expected	[-4.9, 4.9]	[-12.3, 12.4]
Observed	[-3.5, 3.5]	[-8.5, 8.5]



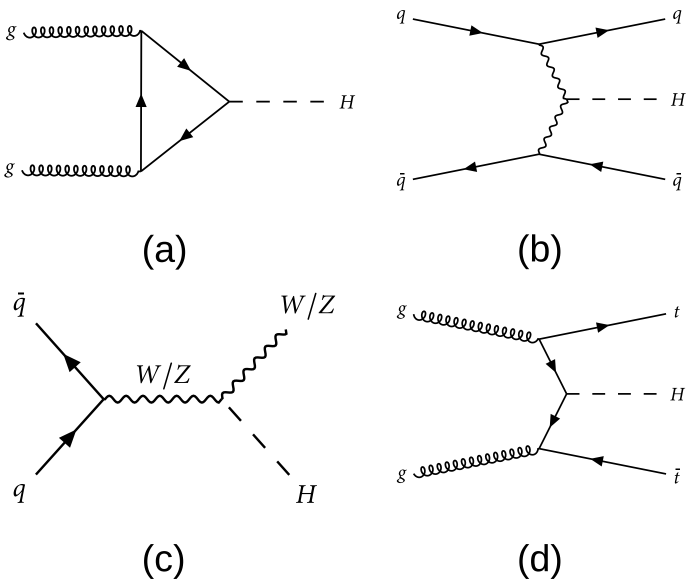


Summary

- Full Run 2 VH, H→cc search is performed, with all three lepton channels and background control regions compared to previous ZH(cc) 36 fb^{-1} analysis
- Diboson measurements:
  - VW(cl): 3.84 σ obs (4.60 σ exp)
  - VZ(cl): 2.61 σ obs (2.24 σ exp)
- **Observed limit of 26 x SM on VH(cc) (for 31 x SM expected)**
  Current best limit on VH(cc)
- κ_c @ 95% CL with $|\kappa_c| < 8.5$

Backup

Higgs production mechanisms and H➔cc search strategies



Main Higgs production processes (Production cross section: σ_H = 56 pb at 13 TeV)

- (a) Gluon fusion (87% of σ_H)
  - Large QCD background
- (b) Vector boson fusion (VBF) (7% of σ_H)
  - S/B is small
- **(c) Associated production with W/Z (4% of σ_H)**
  - **W/Z leptonic decay can be used to trigger the signal**
- (d) Associated production with ttbar (1% of σ_H)
  - Semi-leptonic decay product of top can be used to trigger the signal

Samples

- Data
  - pp collision data recorded by the ATLAS detector during Run 2 of LHC from 2015 to 2018 at a centre-of-mass energy of 13 TeV
  - Corresponding to integrated luminosity of 139 ± 2.4 fb^{-1}
  - Collected with a suite of MET (0L, 1L), single-electron and single-muon triggers (1L, 2L)
  - Events are required to be of good quality and recorded while all relevant detector components were in operation

- 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 + 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

All samples of simulated events were passed through the ATLAS detector simulation, based on Geant4 and were reconstructed using standard ATLAS reconstruction software

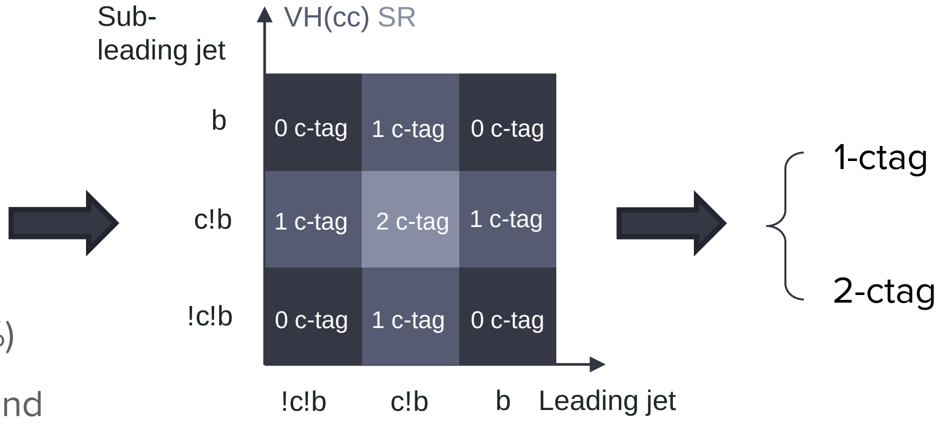
Object and event selection – Object selection

- Leptons
  - Electron
    - pT > 7 GeV and |η| < 2.47
      - loose identification (0L, 2L)
      - tight identification (1L)
  - Muon
    - pT > 7 GeV and |η| < 2.5
      - loose identification (0L, 2L)
      - medium identification (1L)
  - Hadronically decaying tau
    - pT > 20 GeV and |η| < 2.5 except 1.37 < |η| < 1.52
    - medium identification

- Jets
  - reconstructed using anti-kt with R=0.4
    - forward jet
      - pT > 30 GeV and 2.5 < |η| < 4.5
    - central jet
      - pT > 20 GeV and |η| < 2.5
  - **Overlap removal to avoid double counting**
  - Tagging applied
- MET
  - $\vec{E}_T^{\text{miss}} = -\sum\left(\vec{p}_{T,\text{elec}} + \vec{p}_{T,\text{muon}} + \vec{p}_{T,\text{hardronic}-\tau} + \vec{p}_{T,\text{jet}} + \vec{p}_{T,\text{soft term}}\right)$
  - $\vec{p}_T^{\text{miss}}$ track-based MET using all ID tracks associated to the primary vertex

Object and event selection – Tagging

- c-tagging + b-veto WP:
  - **DL1** as a c-tagger
  - b-veto using **MV2c10** 70% WP
- Dedicated optimization of WP:
  - c-jets (27%), b-jets (8.3%), light-jets (1.7%)



Tagging background events

Low statistics

Instead of **D**irectly **T**agging (DT) events, weighting events by the probabilities for each jet to be c-tagged, based on its flavor label, doing ***T**ruth **T**agging* (TT)

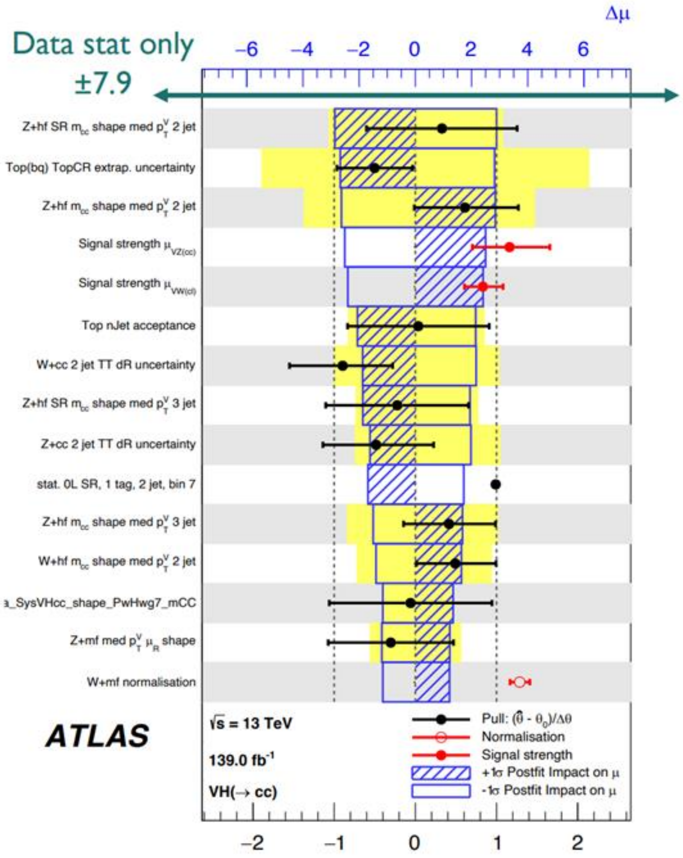
Sample	DT	TT	TT+ΔR(*)
Signal	✓		
Diboson		✓	
Ttbar		✓	
Single Top		✓	
V+jets			✓

(*) ΔR dependent correction

Uncertainties

Major uncertainties:

- Data statistics is the largest
- Z+hf mcc shape (related to Z+bb, Z+cc shape)
- Top(bq) TopCR extrapolation (component peak under VH(cc) signal)
- W/Z+cc 2 jet TT dR (related to W/Z+jets dR correction)
- W+hf mCC shape (related to W+bb, W+cc shape)



Breakdown of uncertainties

- Uncertainty on VH(cc) ~ 15.3
- Stat and systematic uncertainties of the same order
- Largest contributions to systematic uncertainties:
  - Z+jets
  - Top
  - Flavour tagging

Set of NPs	Impact
Total	± 15.3
Data Stat	± 10.0
Data stat only	± 7.9
Float. norm	± 5.1
Full Syst	± 11.5
VH(cc) modelling	± 2.1
Background modelling	± 8.8
W+jets	± 2.9
Z+jets	**± 7.0**
Top	**± 3.9**
Diboson	± 1.00
Multi-jet	± 0.98
Hbb	± 0.78

Experimental Syst (except FTAG)	± 2.96
Lepton	± 0.49
MET	± 0.18
JET	± 2.84
Pile-up/Lumi	± 0.29
FTAG + TT	± 4.29
FTAG (b-jet)	± 1.11
FTAG (c-jet)	± 1.67
FTAG (l-jet)	± 0.35
FTAG (tau-jet)	± 0.33
TT ΔR	± 3.33
DT norm	± 1.74
MC Stat	**± 4.23**

Comparison VHcc 139/fb vs ZHcc 36/fb

	2015+2016 (36 /fb)	Full Run 2
Flavour tagging	c-tagging (MV2 based)	c-tagging **+ b-tag veto** (DL1 vs MV2 based)
Jets categories	2+jets	**2 and 3+jets**
pTV	Low and high pTV	Low and high pTV
SRs	1 c-tag and 2 c-tag	1 c-tag and 2 c-tag
CRs	Top emu	Top emu, **High dR CR, 0 c-tag**
VH(bb) treatment	SM bkg SR Overlap	SM bkg **Orthogonality in SR**
VH(bb) fraction in 2 c-tag	6%	**0,7%**
Truth tagging	ΔR(jet1,jet2)	**Min ΔR(tagged jet, closest jet2)**
FTAG calibrations	36/fb	**140/fb, 80/fb for c-jets**
Modelling	36/fb	**140/fb**

Object and event selection – Object Selection – Jets

Muon-in-jet correction

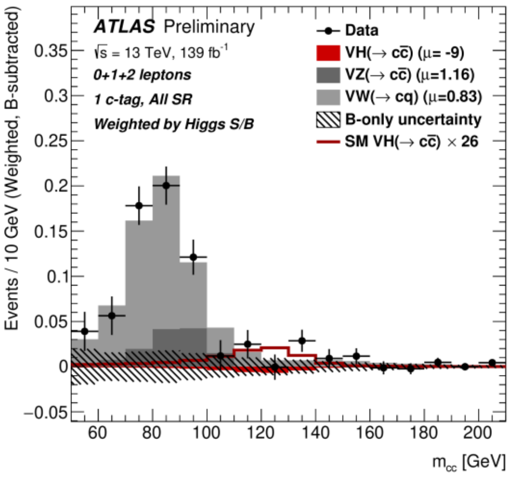
- Apply the correction if
  - muon pT > 4 GeV, |η| < 2.7
  - pass Medium quality cut
  - $\Delta R(\text{jet, muon}) < \min(0.4, 0.04+10/p_T^{\mu})$
- Improve VH(cc) signal resolution up to 6%

Add the muon 4-vector to the jet 4-vector, and remove the energy deposited by the muon from the jet 4-vector

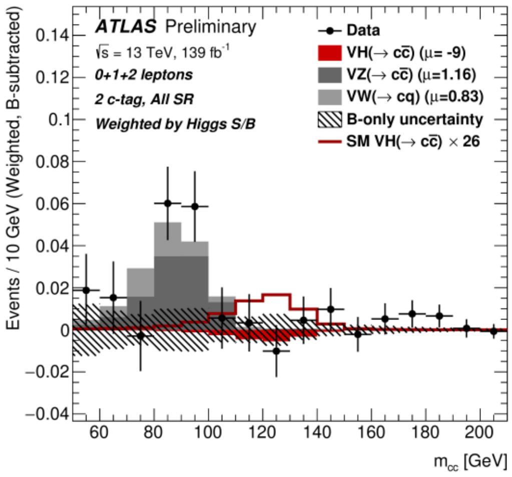
$$\text{vec}_{\text{jet}} = \text{vec}_{\text{jet}} + \text{vec}_{\text{muon}} - \text{dep}_{\text{muon}}$$

Background subtracted plots

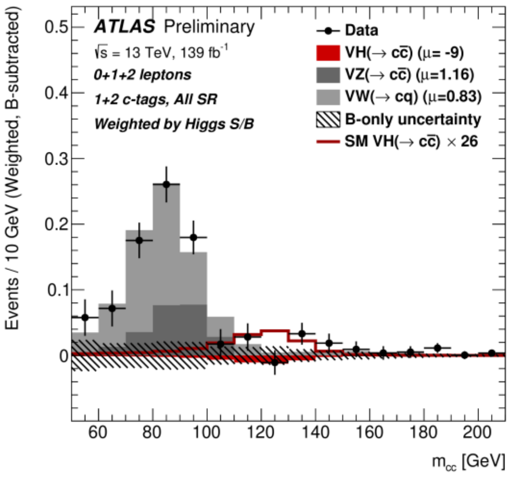
Background subtracted mass spectrum from unconditional 3 POI fit to data



1 c-tag



2 c-tag

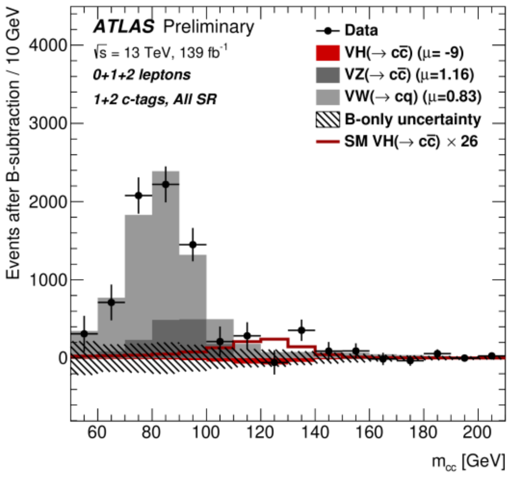


1+2 c-tag

Good Data/MC post-fit agreement

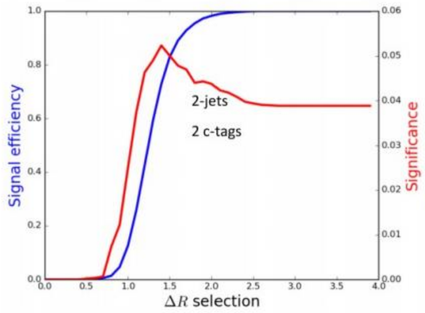
Background subtracted plots

Background subtracted mass spectrum from unconditional 3 POI fit to data

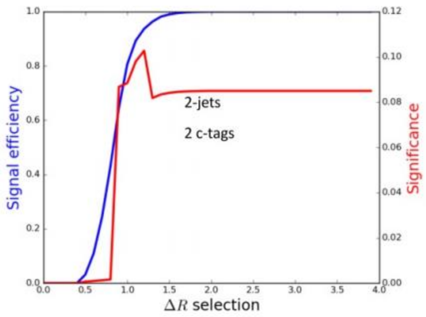


Good Data/MC post-fit agreement

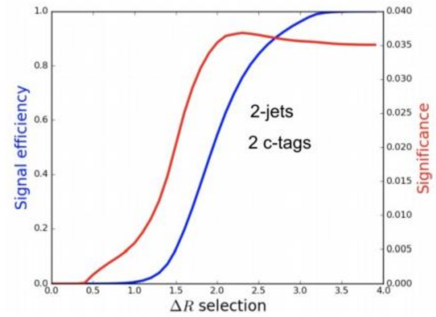
dR selection



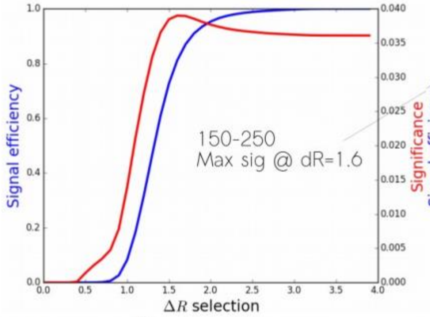
(a) 0-lepton: p_T^V: $150 - 250\ GeV$



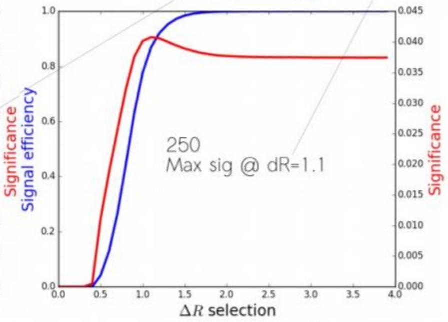
(b) 0-lepton: p_T^V: $\geq 250\ GeV$



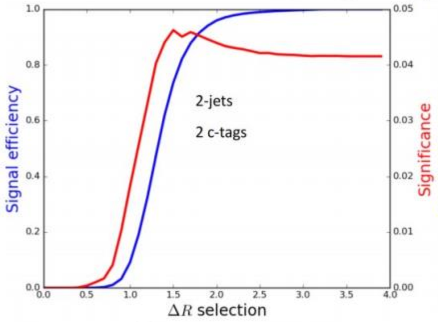
(e) 2-lepton: p_T^V: $75 - 150\ GeV$



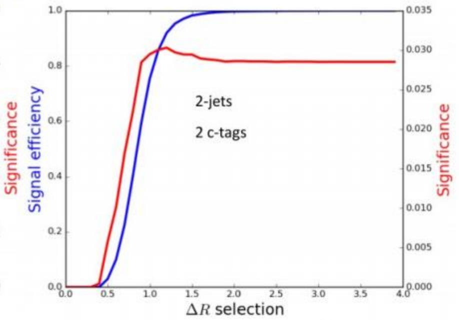
(c) 1-lepton: p_T^V: $150 - 250\ GeV$



(d) 1-lepton: p_T^V: $\geq 250\ GeV$



(f) 2-lepton: p_T^V: $150 - 250\ GeV$



(g) 2-lepton: p_T^V: $\geq 250\ GeV$

Overlap removal

- **tau-electron:** If $\Delta R(\tau, e) < 0.2$, the τ lepton is removed.

- **tau-muon:** If $\Delta R(\tau, \mu) < 0.2$, the τ lepton is removed, with the exception that if the τ lepton has $p_{\mathrm{T}} > 50$ GeV and the muon is not a combined muon, then the τ lepton is not removed.

- **electron-muon:** If a combined muon shares an ID track with an electron, the electron is removed. If a calo-tagged muon shares an ID track with an electron, the muon is removed.

- **electron-jet:** If $\Delta R(\mathrm{jet}, e) < 0.2$ the jet is removed. For any surviving jets, if $\Delta R(jet, e) < \min(0.4, 0.04 \ + \ 10\ GeV/p_{\mathrm{T}}^{e})$, the electron is removed.

- **muon-jet** If $\Delta R(jet, \mu) < 0.2$ or the muon ID track is ghost associated to the jet, then the jet is removed if the jet has less than three associated tracks with $p_{\mathrm{T}} > 500$ MeV ($\mathrm{N}umTrkPt500PV^{jet} \ < \ 3$) or both of the following conditions are met: the p_{T} ratio of the muon and jet is larger than 0.5 ($p_{\mathrm{T}}^{\mu}/p_{\mathrm{T}}^{\mathrm{jet}} > 0.5$) and the ratio of the muon p_{T} to the sum of p_{T} of tracks with $p_{\mathrm{T}} > 500$ MeV associated to the jet is larger than 0.7 ($p_{\mathrm{T}}^{muon}/SumPtTrkPt500PV^{jet} \ > \ 0.7$). For any surviving jets, if $\Delta R(\mathrm{jet}, \mu) < \min(0.4, 0.04 + 10\ \mathrm{GeV}/p_{\mathrm{T}}^{\mu})$, the muon is removed.

- **tau-jet:** If $\Delta R(\tau, \mathrm{jet}) < 0.2$, the jet is removed.

C-tagging

Variable Name	Description
L_{xyz}	Three-dimensional displacement of secondary vertex from the primary vertex
L_{xy}	Transverse displacement of the secondary vertex
$Y_{\mathrm{trk}}^{\mathrm{min}}$,$Y_{\mathrm{trk}}^{\mathrm{max}}$,$Y_{\mathrm{trk}}^{\mathrm{avg}}$	Min, Max and Avg. track rapidity of tracks in jet
$Y_{\mathrm{trk}}^{\mathrm{min}}$,$Y_{\mathrm{trk}}^{\mathrm{max}}$,$Y_{\mathrm{trk}}^{\mathrm{avg}}$ (2^{nd} vtx)	Min, Max and Avg. track rapidity of tracks at secondary vertex
m	Invariant mass of tracks associated to secondary vertex
E	Energy of charged tracks associated to secondary vertex
$\mathrm{f_E}$	Energy fraction of charged tracks (from all tracks in the jet) associated to secondary vertex
$\mathrm{N_{trk}}$	Number of tracks associated to the secondary vertex

Table 2: Summary of new input variables, used for charm tagging, in addition to those used by the baseline MV2 *b*-tagging algorithm [4]. The track pseudo-rapidity Y_{trk} is computed as $Y_{\mathrm{trk}} \equiv -\log\left(\tan\left(\frac{\theta}{2}\right)\right)$, where θ is the angle between the track momentum and the hadron flight path reconstructed by JetFitter.

Tagging working point

	c-jets	b-jets	l-jets
ZH(cc) 36 /fb	41%	25%	5%
VH(cc) 139 /fb	27%	8%	1.6%
CMS VH(cc) 36 /fb	27%	17%	4%

Systematics pruning

- Neglect the normalization uncertainty for a given sample in a region if either of the following is true
  - the variation is less than 0.5%
  - both up and down variations have the same sign
- Neglect the shape uncertainty for a given sample in a given region if the following is true
  - not one single bin has a deviation over 0.5% after the overall normalization is removed
  - if only the up or the down variation is non-zero and passed the previous pruning steps
- Neglect the shape and normalization uncertainties for a given sample in a given region if the sample is less than 2% of the total background
  - if the signal $<$ 2% of the total background in all bins and the shape and normalization error are each $<$ 0.5% of the total background
  - if at least one bin has a signal contribution $>$ 2% of the total background, only in those bins where the shape and normalization error are each $<$ 2% of the signal yield

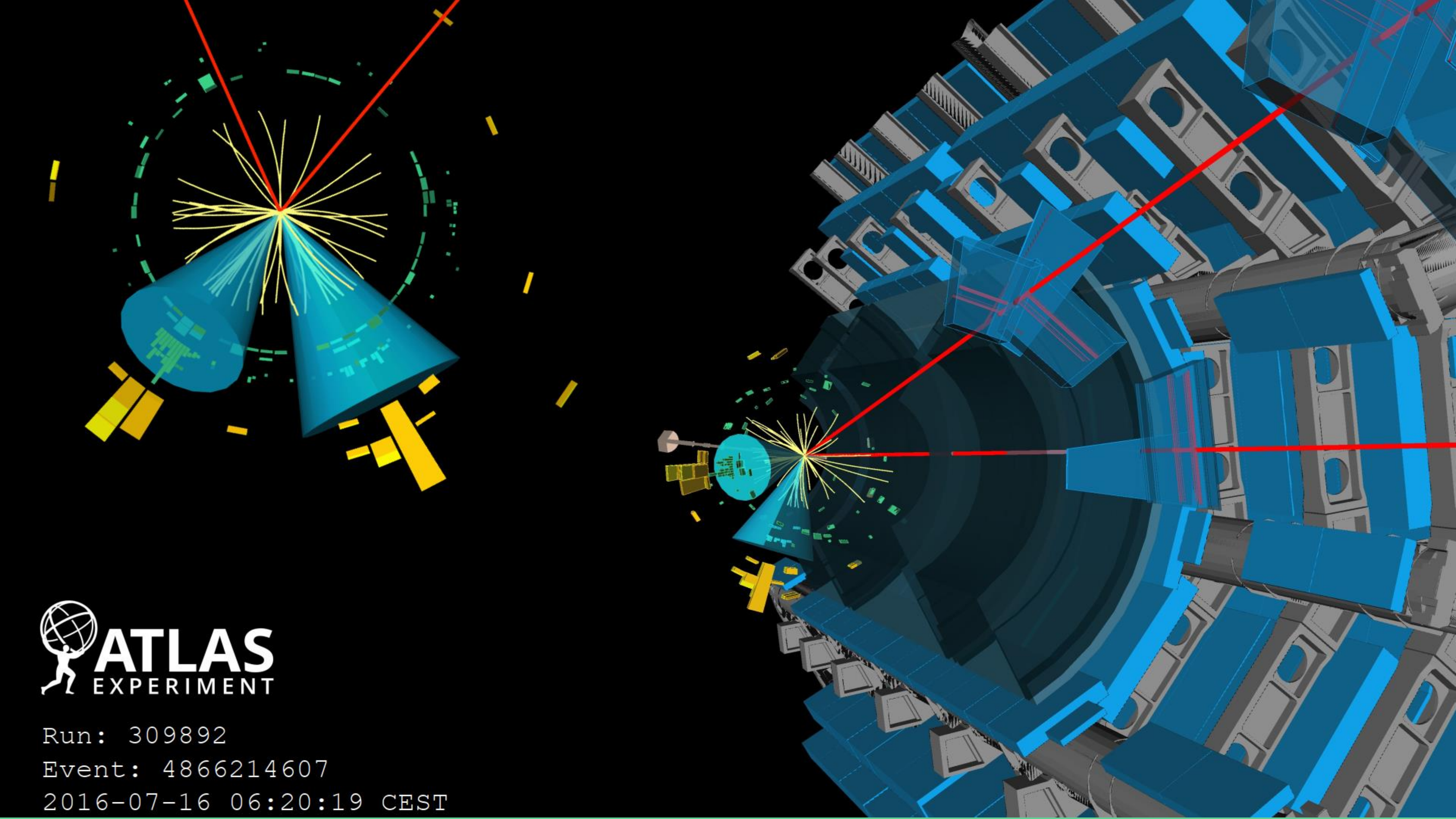
Higgs Lagrangian

- $\mathcal{L}_{\mathrm{GM}} = \frac{1}{4} g^2 v^2 W_\mu^+ W^{-\mu} + \frac{1}{8} v^2 \left(g^2 + g'^2\right) Z_\mu Z^\mu \Rightarrow m_Z = \frac{1}{2} v \sqrt{g^2 + g'^2}, \frac{m_W}{m_Z} = \cos\theta$
- $\mathcal{L}_{\mathrm{Yukawa}} = -\left[\frac{m_{li}}{v} \overline{l_i} l_i + \frac{m_{di}}{v} \overline{d}_i d_i + \frac{m_{ui}}{v} \overline{u}_i u_i\right] H - m_{li} \overline{l_i} l_i - m_{di} \overline{d}_i d_i - m_{ui} \overline{u}_i u_i$

$$m_{li} \equiv \frac{g_i^L}{\sqrt{2}} v, m_{di} \equiv \frac{g_i^d}{\sqrt{2}} v, m_{ui} \equiv \frac{g_i^u}{\sqrt{2}} v$$

Anti QCD cuts

- $|\Delta\Phi(\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathbf{E}_{\mathrm{T,\,trk}}^{\mathrm{miss}})| < 90\,^\circ$
- $|\Delta\Phi(jet1, jet2)| < 140\,^\circ$
- $|\Delta\Phi(\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}, h)| > 120\,^\circ$
- $min[|\Delta\Phi(\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{pre-sel. jets})|] > 20\,^\circ$ for 2 jets, $> 30\,^\circ$ for 3 jets.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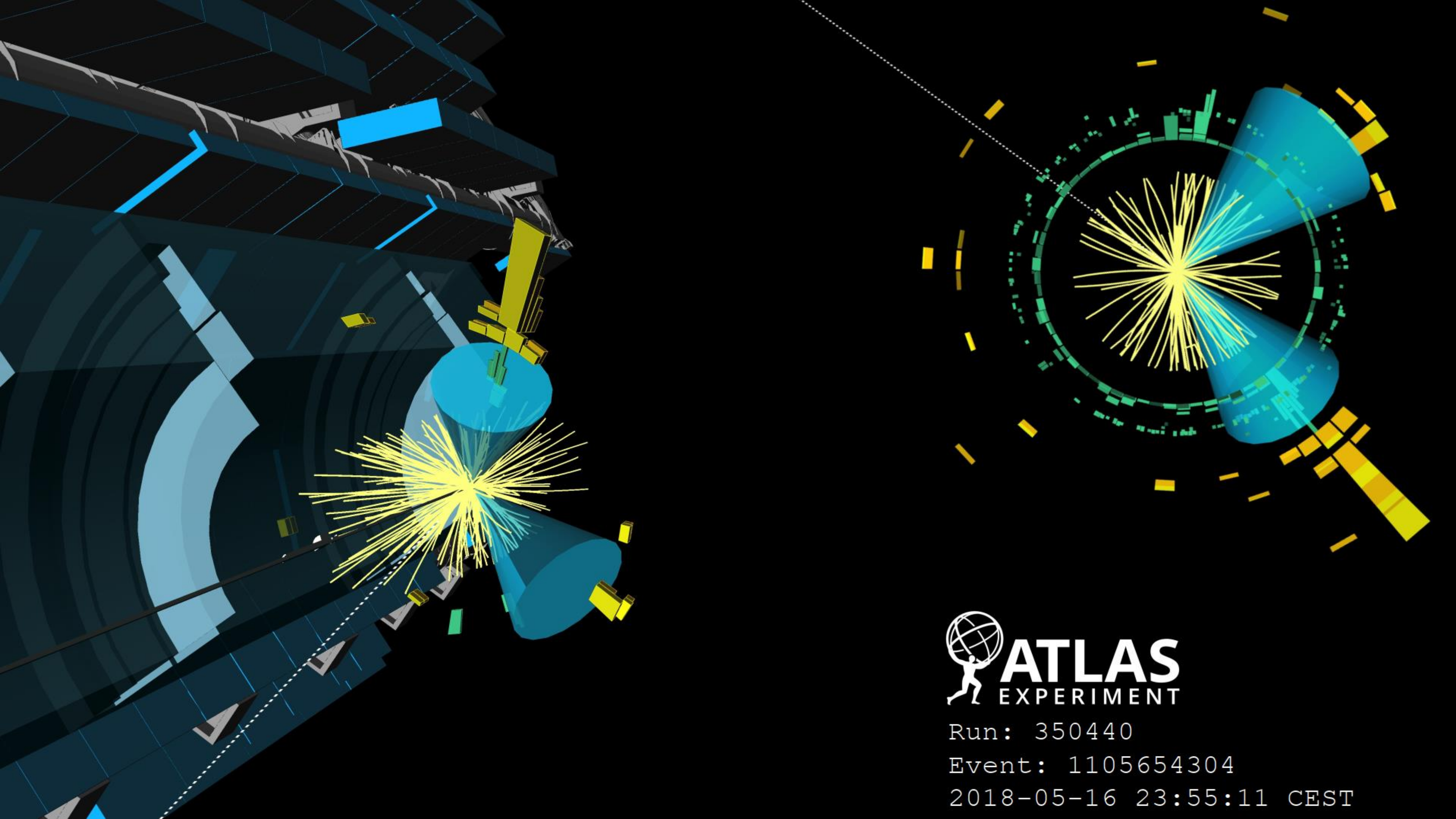
2016-07-16 06:20:19 CEST


ATLAS
EXPERIMENT
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Event: 1105654304
2018-05-16 23:55:11 CEST

Tagging

"c-tag + b-veto" working point calibrated using the same control channels and methods used for official b-tagging calibrations (exactly the same code used)

- b-jets calibrated in $e^{\pm}\mu^{\mp} + 2$ jets region pure in di-leptonic events, uncertainty dominated by modelling uncertainties
- c-jets calibrated in $\ell^{\pm} + 2$ jets $+ 2$ b-jets pure in semi-leptonic events ($W \to cs, cd$), uncertainty dominated by modelling uncertainties
- light flavour jets calibrated in $Z+$ jets events using "negative tag" method, uncertainty dominated by "extrapolation" uncertainty from negative tag approach
- τ-jets share scale factor derived for c-jets, with additional uncertainty of 22%

Single top