Probing charm Yukawa coupling using ATLAS detector

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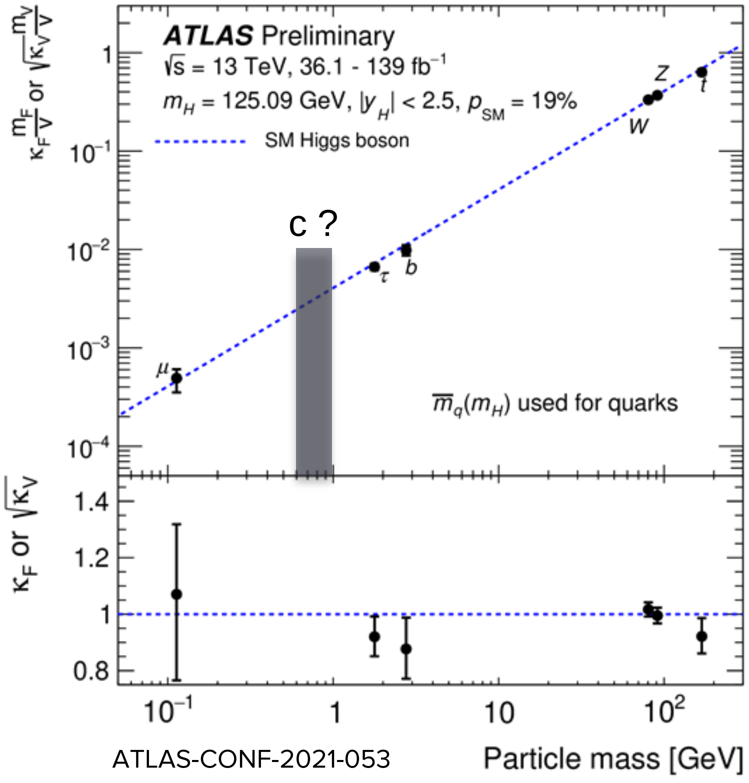
CLHCP 2021, Nov 25-28

ATLAS-CONF-2021-021

Motivation for H➔cc



ATLAS-CONF-2021-053

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.

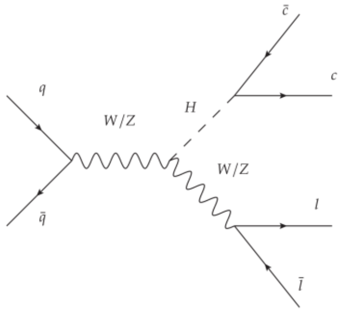
H➔cc is the most direct channel to measure κ_c (y_c/SM).

- κ_c can be modified in BSM models (2HDM, HVT, ...)

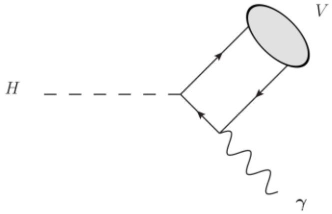
(*) Charm quark Yukawa coupling constant

Overview

VH→cc



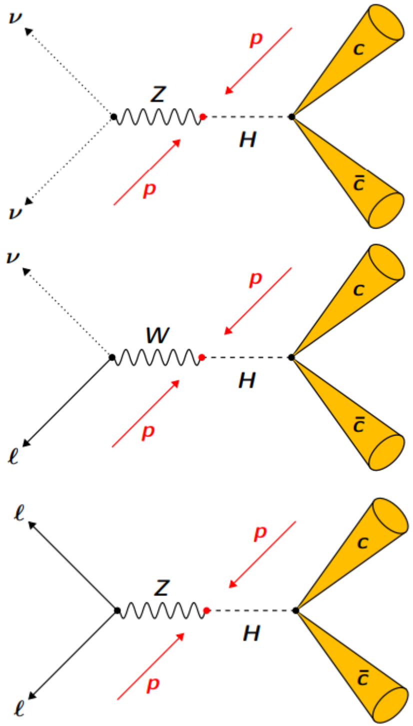
H→J/ψ + γ



- Phys. Rev. Lett. 120 (2018) 211802
  - Previous ATLAS Z(l+l-)Hcc result with 36 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 36 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 large-R 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 **125 x SM** *Phys. Lett. B 786 (2018) 134*, CMS **642 x SM** *Phys. Lett. B 797 (2019) 134811*

VH(H→cc) search strategy



0 lepton

1 lepton

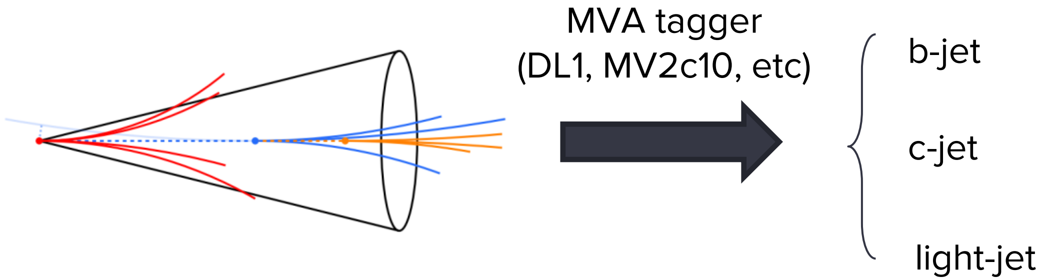
2 lepton

- 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) categorized in several p_T^V 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

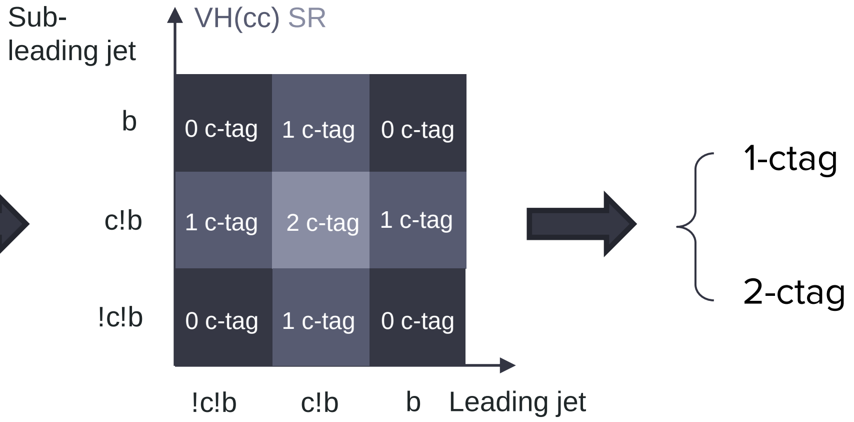
p_T^V – *transverse momentum of the vector boson*
(*) only in 2 lepton channel

Tagging



- 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%)

EPJC 79 (2019) 970



Event selection

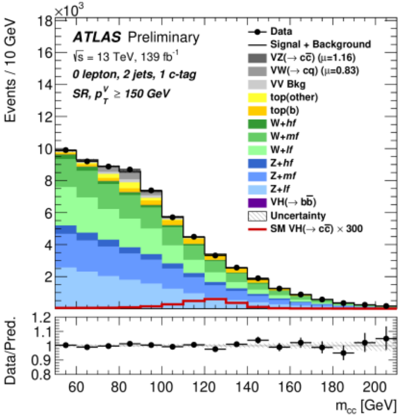
- Region-specific selections
- Common selections

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

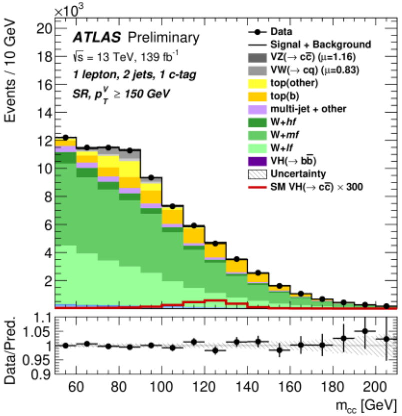
Common Selections	
Central jets	≥ 2
Signal jet p_T	≥ 1 signal jet with $p_T > 45$ GeV
c-jets	1 or 2 c-tagged signal jets
b-jets	No b-tagged non-signal jets
Jets	2, 3 (0- and 1-lepton), 2, ≥ 3 (2-lepton)
p_T^V regions	75–150 GeV (2-lepton) >150 GeV
$\Delta R(\text{jet 1, jet 2})$	$75 < p_T^V < 150$ GeV: $\Delta R \leq 2.3$ $150 < p_T^V < 250$ GeV: $\Delta R \leq 1.6$ $p_T^V > 250$ GeV: $\Delta R \leq 1.2$

Signal regions

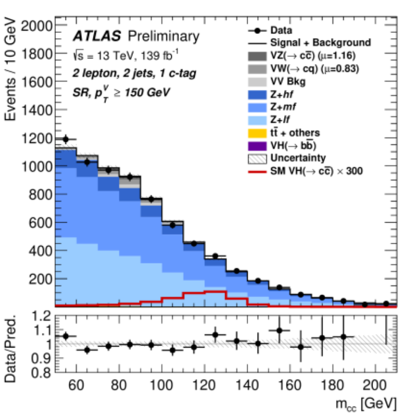
0 lepton selected SRs

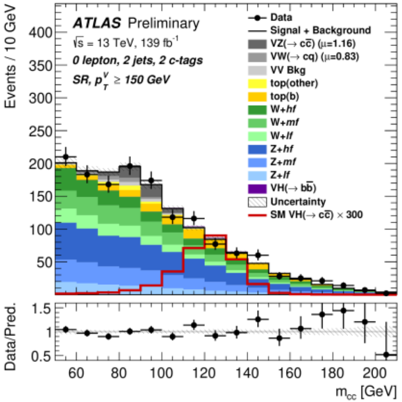


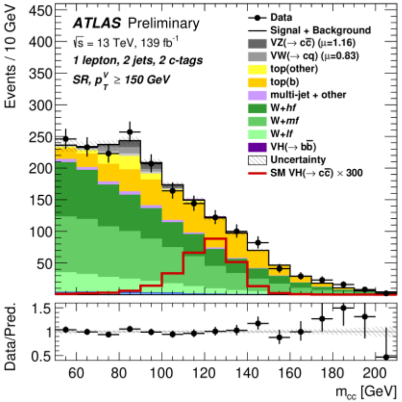
1 lepton selected SRs

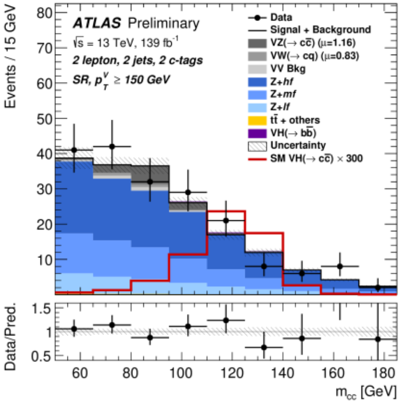


2 lepton selected SRs









Main backgrounds:

0 lepton

Z+jets | W+jets | Top

1 lepton

W+jets | Top

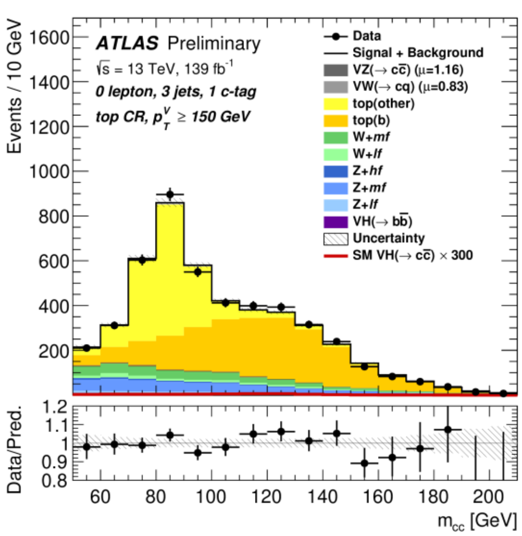
2 lepton

Z+jets | Diboson

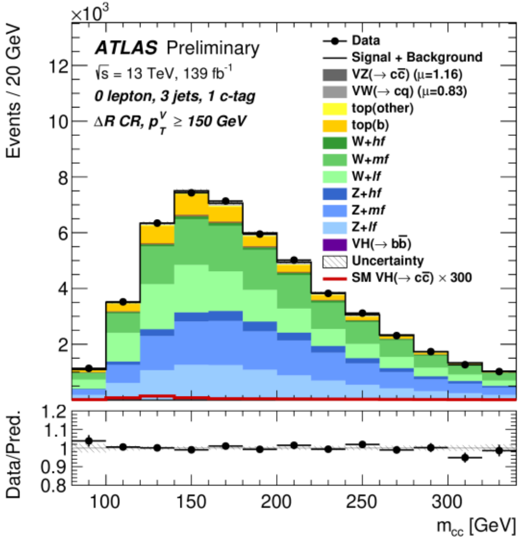
Flavour treatment:

- **V+jets** split according to jets flavour: **V+hf** (cc, bb), **V+mf** (cl, bl, bc) and **V+lf**
- **Diboson** split by decays: **VZ (Z→cc)**, **VW (W→cq)** and **VV bkg**
- **Top** (ttbar and Wt) as:
  - **top(b)** – ≥ 1 jet from b-quark
  - **top(other)** – jets from W boson

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

Uncertainties

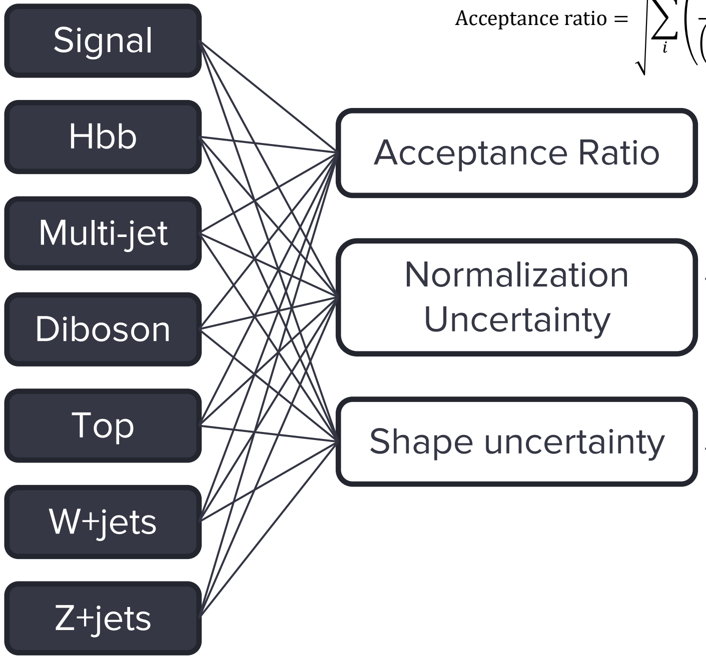
Experimental uncertainties:

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

(*) weighting events by the probabilities for each jet to be c-tagged

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

Fit strategy

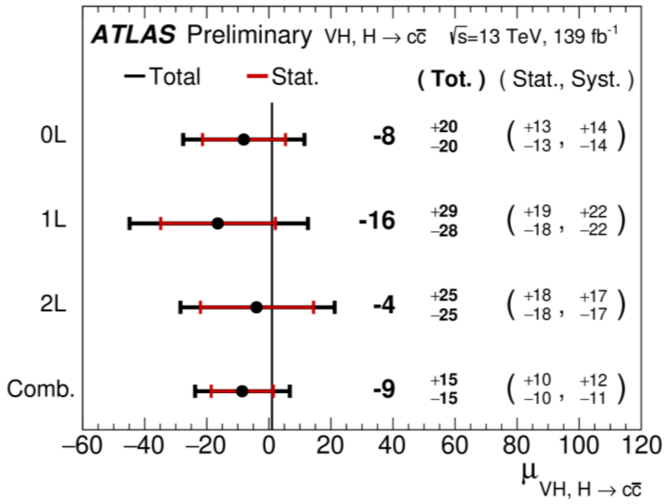
$$\mathcal{L}(\boxed{\mu}, \vec{\theta}, \vec{\gamma}\,) = \prod_{i \in \text{bins}} \boxed{\text{Pois}\left(N_i \middle| \boldsymbol{\mu} s_i(\vec{\theta}) + \boldsymbol{\gamma}_i b_i(\vec{\theta})\right)} \times \prod_{\theta \in \vec{\theta}} \boxed{\frac{1}{\sqrt{2\pi}} e^{-\theta^2/2}} \times \prod_{i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

POI | Poissonian likelihood | Constraints on NPs | Constraints on MC statistics

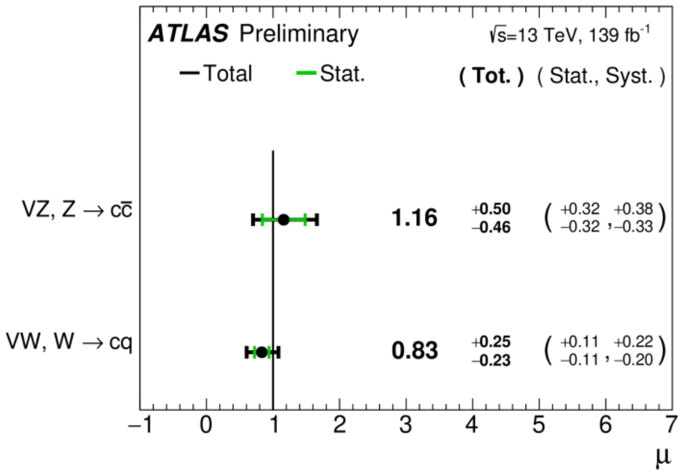
- Simultaneous binned likelihood fit to m_{cc} distributions of the analysis categories (16 SRs and 28 CRs)
- Simultaneously measuring **3 parameters of interest** (POIs): $\mu_{VH(cc)}$, $\mu_{VZ(cc)}$, $\mu_{VW(cq)}$
- **Nuisance Parameters (NPs)**
  - Experimental uncertainties: flavor tagging, jets, leptons, MET, luminosity, pile-up
  - Modelling uncertainties
  - MC statistics uncertainty
- **Floating normalizations of main backgrounds**: Z/W+hf, Z/W+mf, Z/W+lf, top (b) and top (other) in 0 and 1 lepton channels, and ttbar in 2 lepton (from top emu CR)

Best-fit Results

- Signal strengths from the 3 POI fit:
  - VH(cc): -9 +/- 15
  - VW(cl): 0.8 +/- 0.2
  - VZ(cc): 1.2 +/- 0.5
- 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

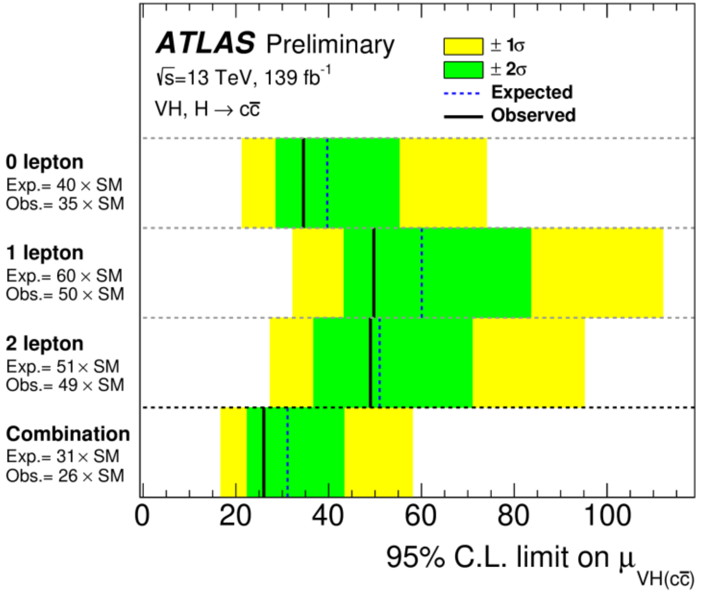
Statistical results

- Observed VH(cc) limit of **26 x SM** (31 x SM expected)
  - Highest sensitivity in 0 lepton channel
- Diboson
  - VW(cq) significance of **3.8 σ** (4.6 σ expected)
  - VZ(cc) significance of **2.6 σ** (2.2 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	4.6 σ	3.8 σ
VZ(cc) significance	2.2 σ	2.6 σ

First in ATLAS

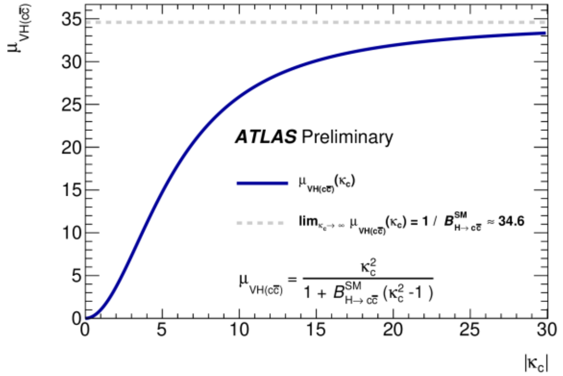


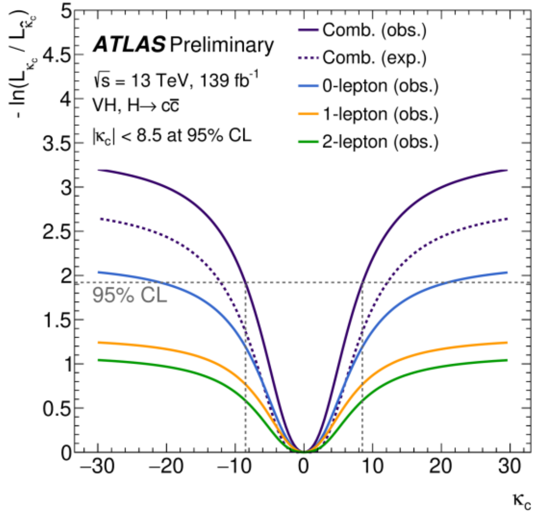
Expected and observed limit in combined fit and with POI decorrelated into channels

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 limit on κ_c at 95% CL $|\kappa_c| < 8.5$

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

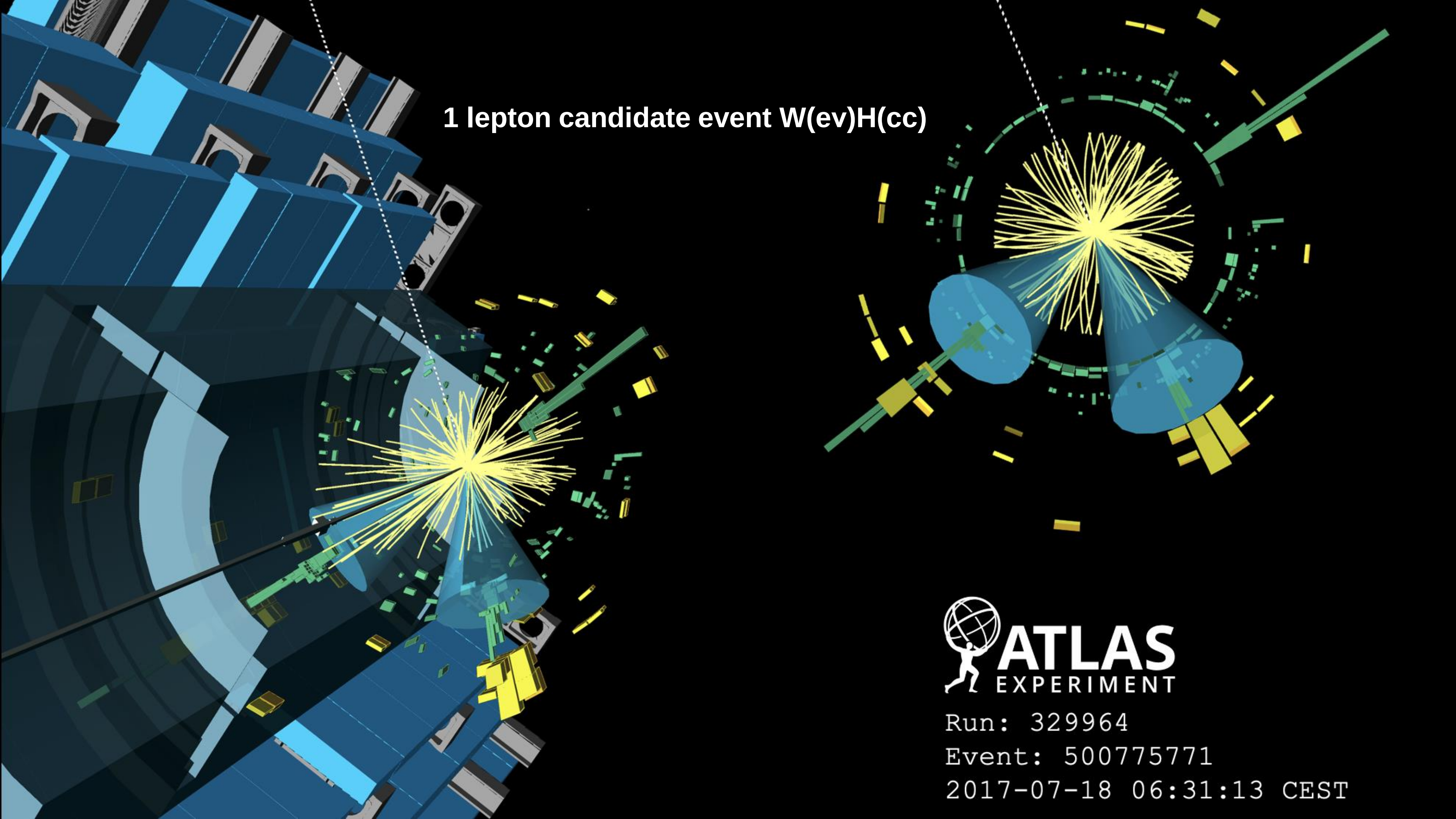




Summary

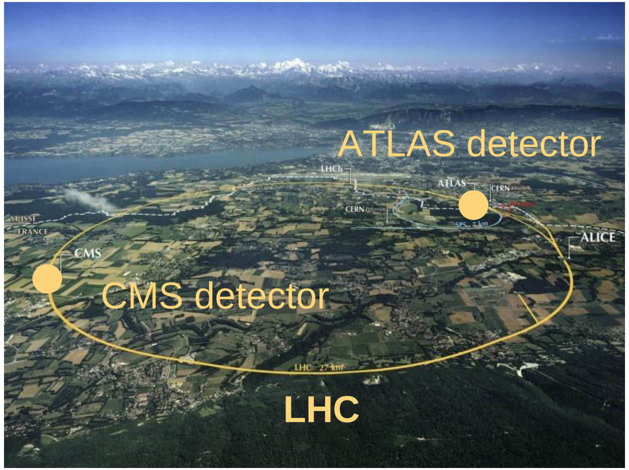
- Full Run 2 VH, $H \rightarrow cc$ search is performed, with all three lepton channels and background control regions compared to previous ZH(cc) 36 fb^{-1} analysis
- Diboson measurements:
  - VW(cq): 3.84 σ obs (4.60 σ exp)
  - VZ(cc): 2.61 σ obs (2.24 σ exp)
- Observed limit of **26 x SM** on VH(cc) (110 x SM for previous ZH(cc) paper)
- κ_c @ 95% CL with $|\boldsymbol{\kappa_c}|$ **< 8.5**, current best limit on κ_c
- New opportunities underway
  - LHC RUN III and HL-LHC
  - Complementary decay channels

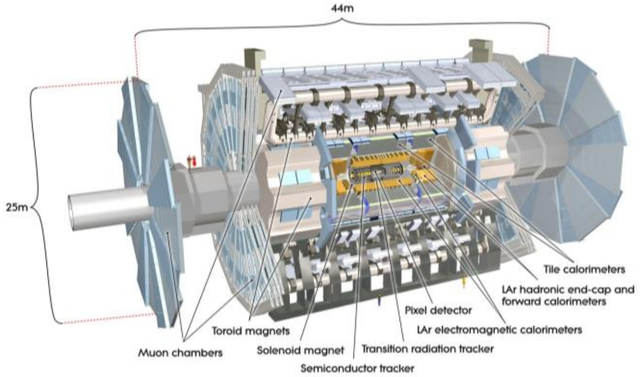
1 lepton candidate event W(ev)H(cc)



Backup

ATLAS detector and Run 2 Data Taking





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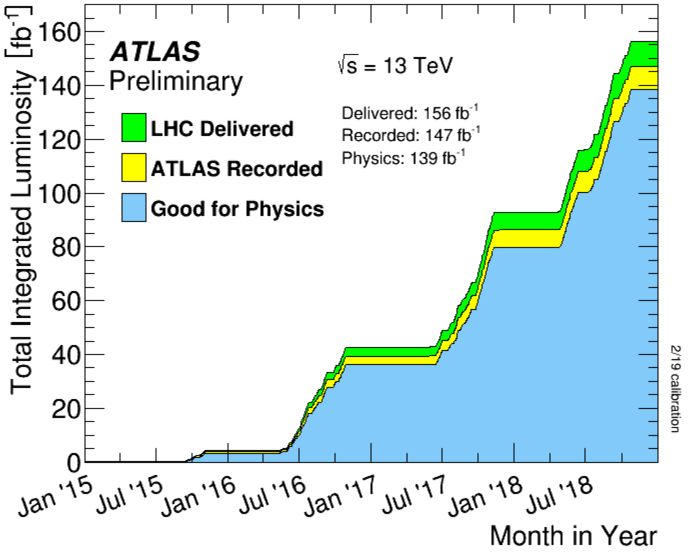
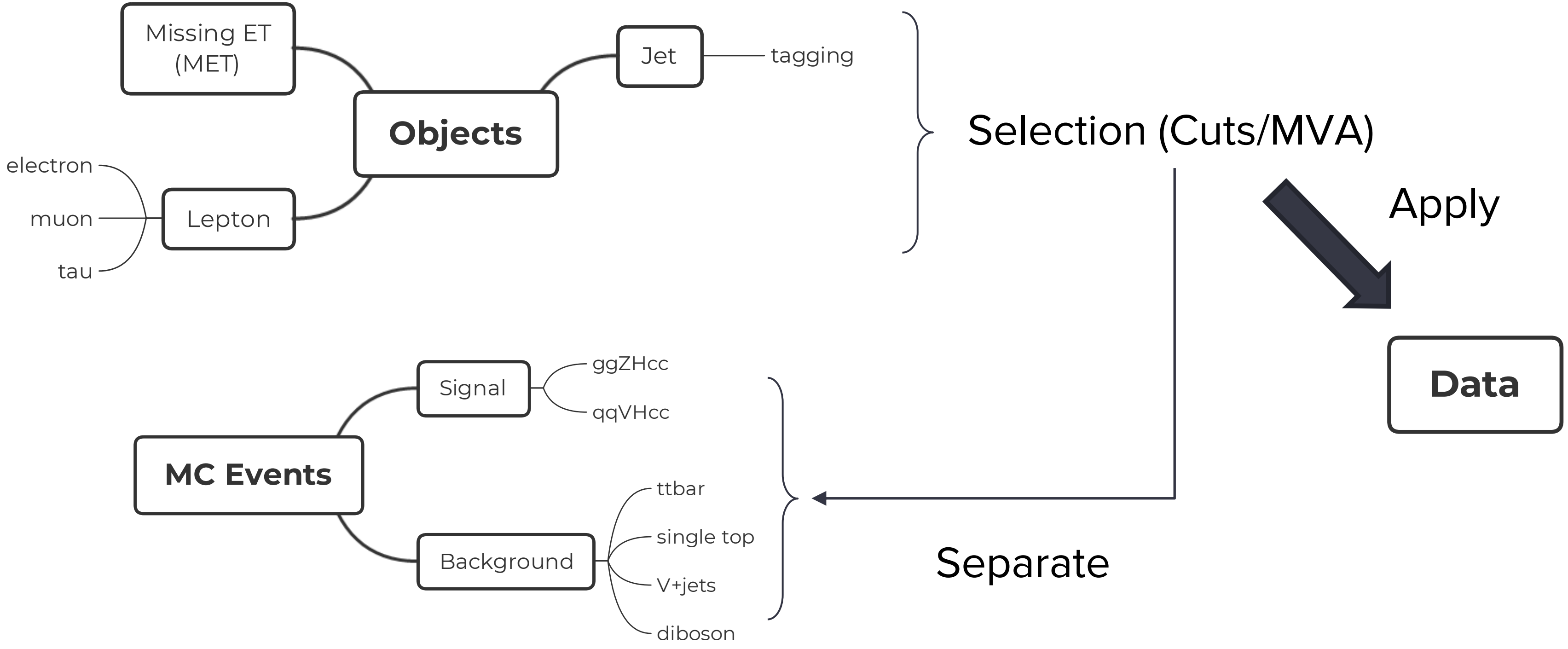
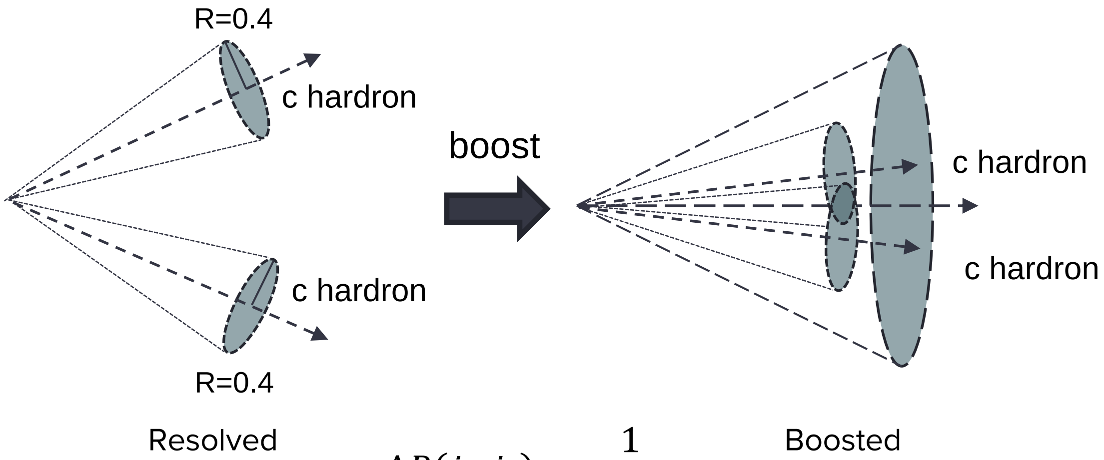


Proton-proton collision at 13 TeV 139 fb^{-1} usable for data analyses

VH(H→cc) analysis syllables



Resolved and boosted



$$\Delta R(j_1, j_2) \propto \frac{1}{p_T^{\mathrm{Higgs}}}$$

Simultaneous profile likelihood binned fit to all regions

Signal strength

Systematic uncertainty

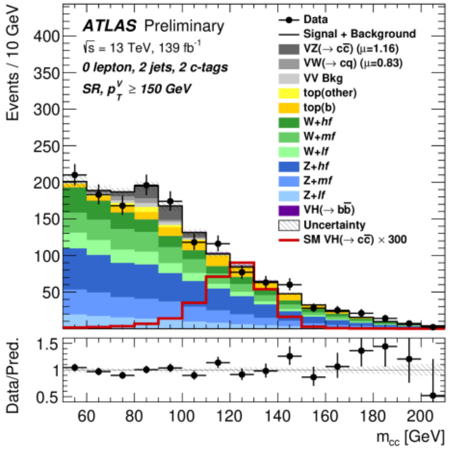
MC statistical uncertainty

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

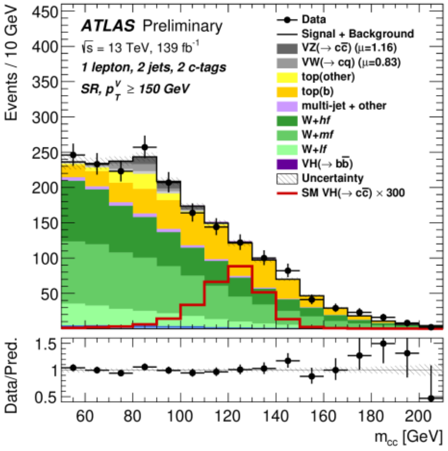
- Control regions are not shown
- 3 parameters of interest (POIs): $\mu_{VH(cc)}$, $\mu_{VZ(cc)}$, $\mu_{VW(cq)}$
- The free-floating normalization factors are not listed in the formula:
  - top background which decay into one **b quark** and one other quark (or tau lepton) (bc, bl, bb, bτ)
  - top background 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)

Post-fit plots and normalization factors

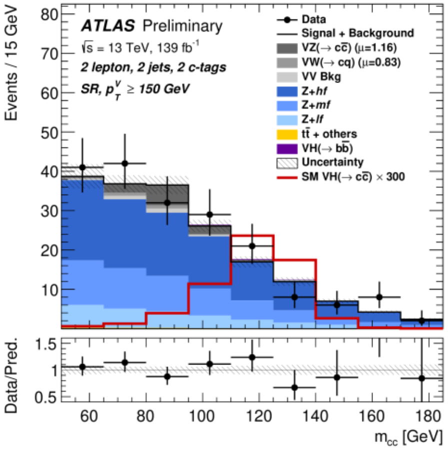
0 Lepton, pTV ≥ 150 GeV



1 Lepton, pTV ≥ 150 GeV

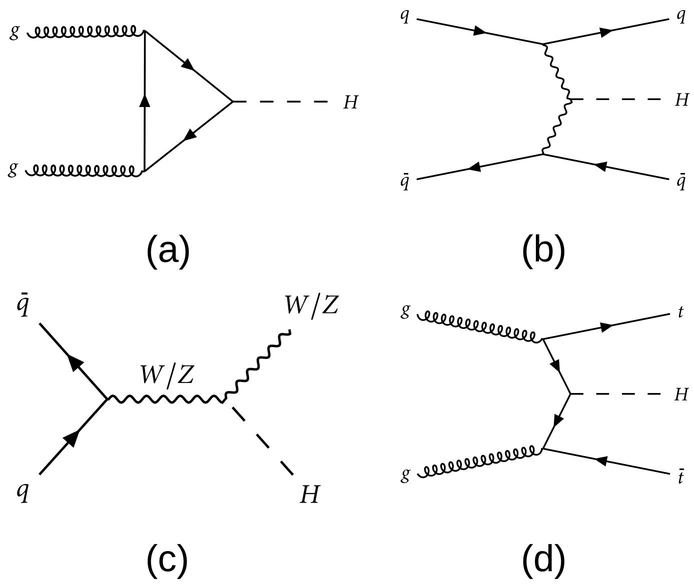


2 Lepton, pTV ≥ 150 GeV



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

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

Truth Flavour Tagging

Select events passed c tagger

1000 events → 20 events

Flavour Tagging

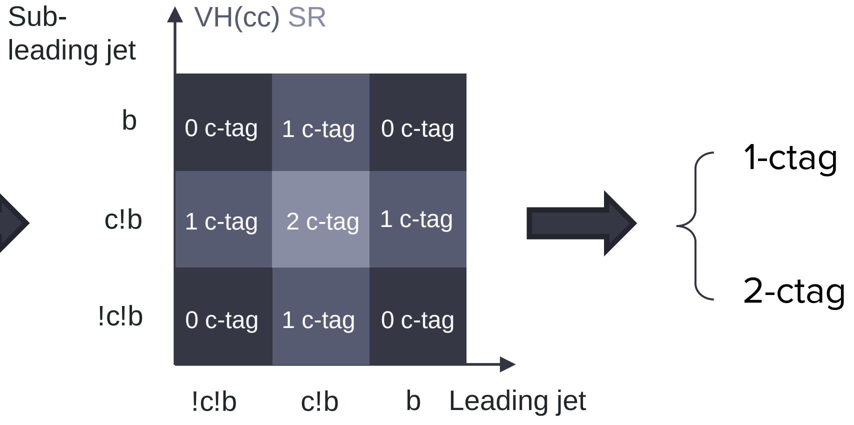
weight events by possibility passing the tagger

1000 events → 1000 weighted events

Truth Flavour Tagging

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

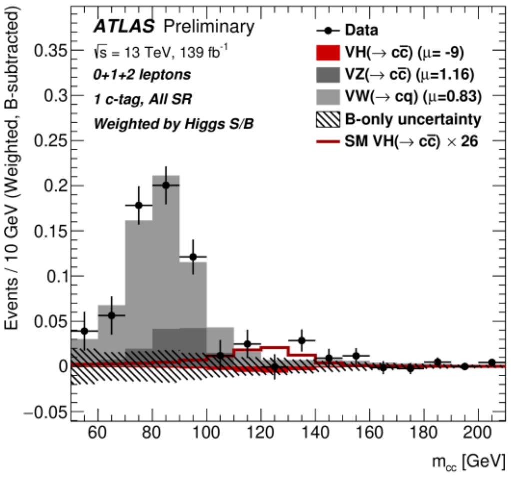
Breakdown of uncertainties

- Statistical and systematic uncertainties of the same magnitude
- Main systematic uncertainties:
  - Background modelling: V+jets and top
  - Simulation statistics
  - Truth-flavour tagging (TT)
    - ΔR dependent correction applied for V+jets
    - Small remaining Direct Tagging/TT non-closure:
      - Correction of TT yields to match DT
      - Additional norm-only systematic uncertainty
    - Use of truth-tagging represents nevertheless 10% improvement on limit w.r.t direct tagging
- Possible improvements with more simulated events and use of latest MC generators

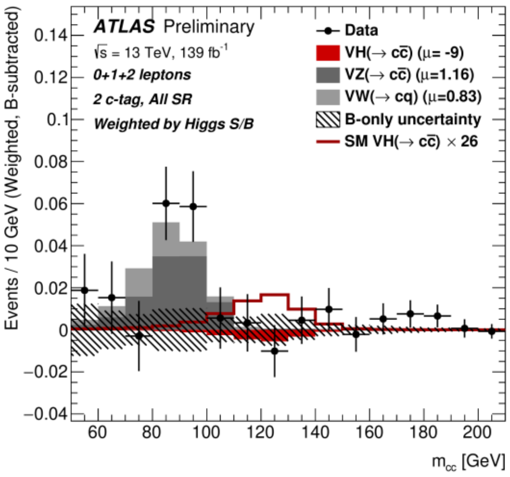
Source of uncertainty		$\mu_{VH(c\bar{c})}$	$\mu_{VW(cq)}$	$\mu_{VZ(c\bar{c})}$
Total		15.3	0.24	0.48
Statistical		10.0	0.11	0.32
Systematics		11.5	0.21	0.36
Statistical uncertainties				
Data statistics only		7.8	0.05	0.23
Floating normalisations		5.1	0.09	0.22
Theoretical and modelling uncertainties				
$VH(\rightarrow c\bar{c})$		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
$VH(\rightarrow b\bar{b})$		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

Background subtracted plots

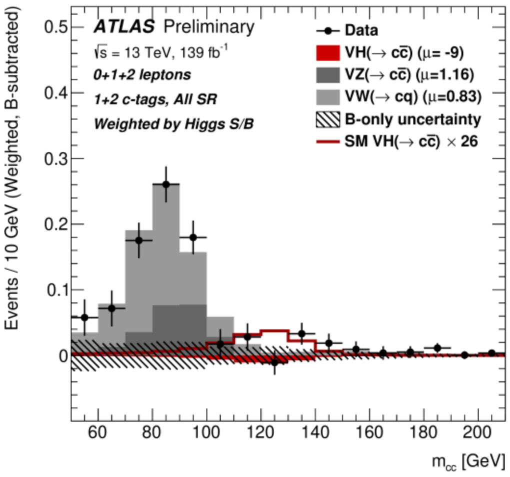
Background subtracted mass spectrum from unconditional 3 POI fit to data



1 c-tag



2 c-tag

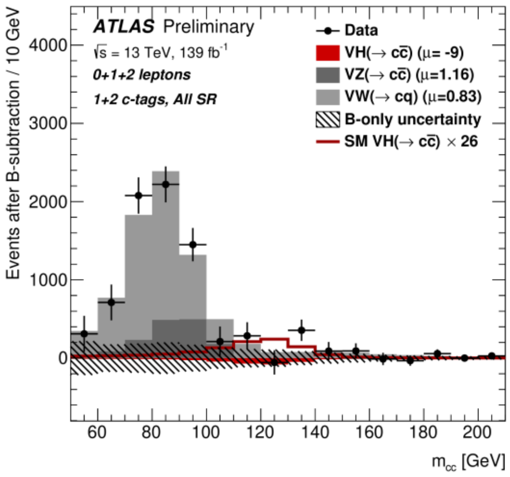


1+2 c-tag

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

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%

Higgs Lagrangian

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

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

1 lepton candidate event W(eν)H(cc)

$\Delta\varphi = -1.37$

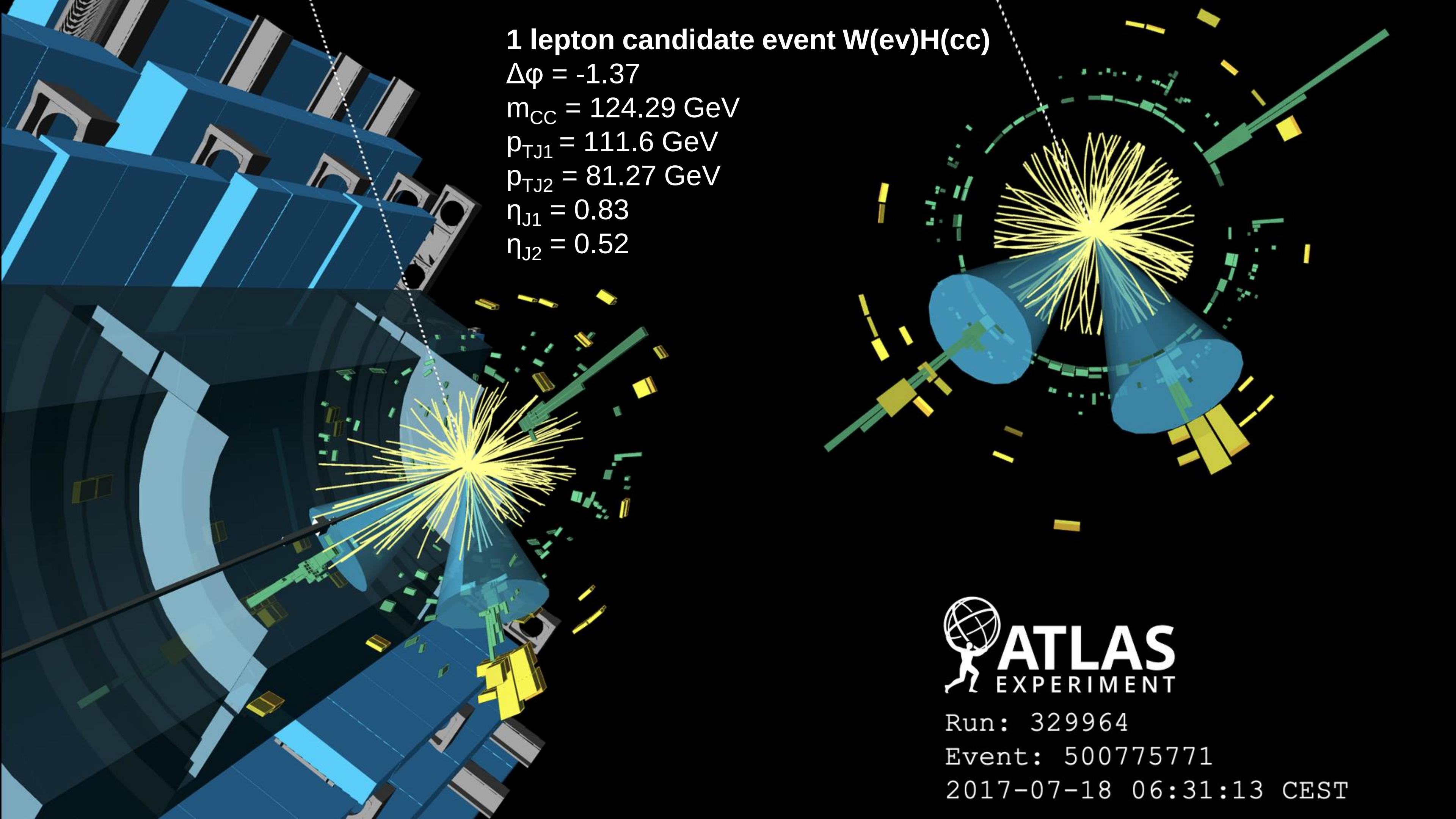
$m_{CC} = 124.29$ GeV

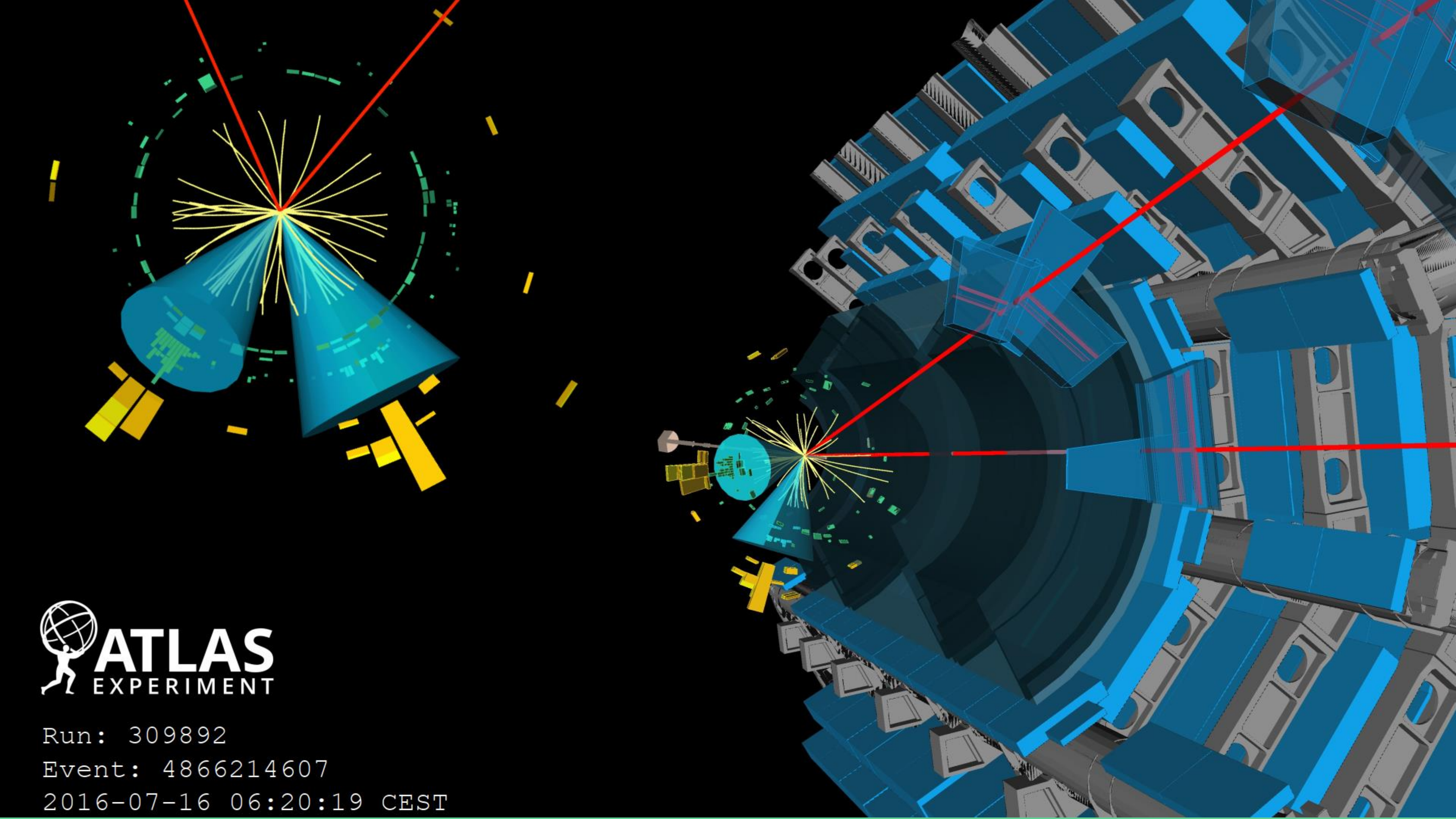
$p_{TJ1} = 111.6$ GeV

$p_{TJ2} = 81.27$ GeV

$\eta_{J1} = 0.83$

$\eta_{J2} = 0.52$

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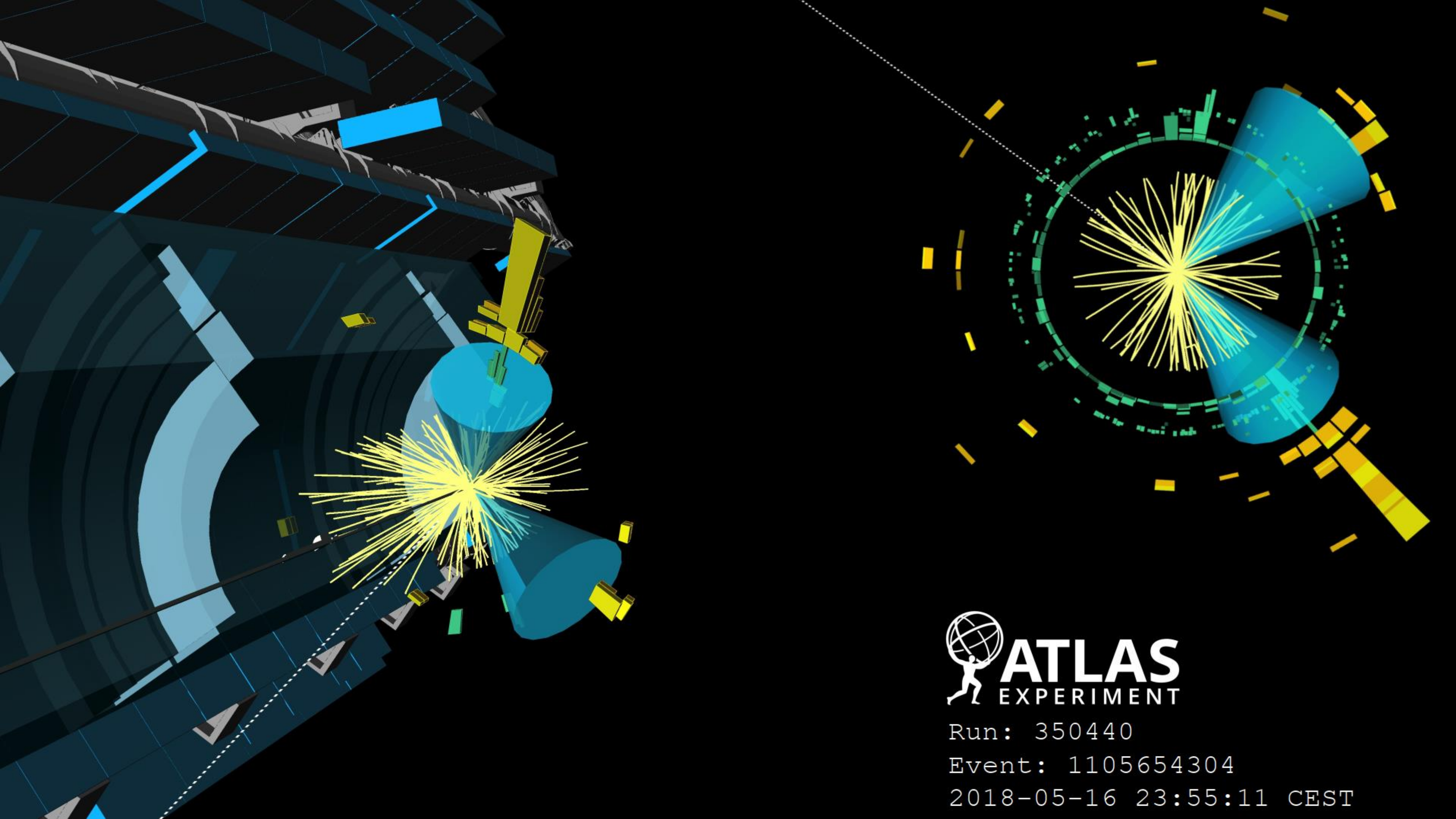
2016-07-16 06:20:19 CEST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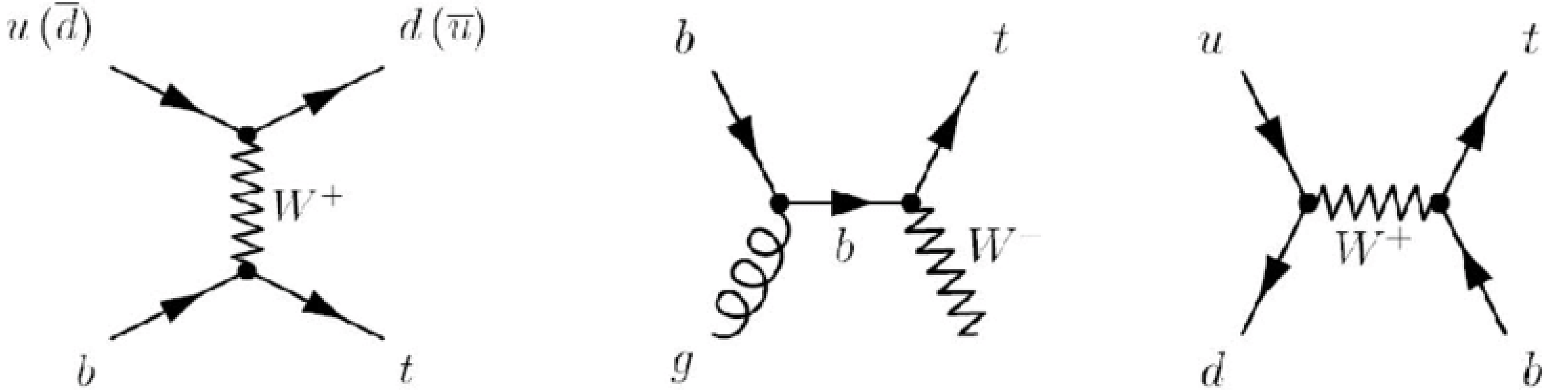
2018-05-16 23:55:11 CEST

Single top



(a) (b) (c)