Measurements of VH(→bb) and VH(→cc) decays with the ATLAS experiment

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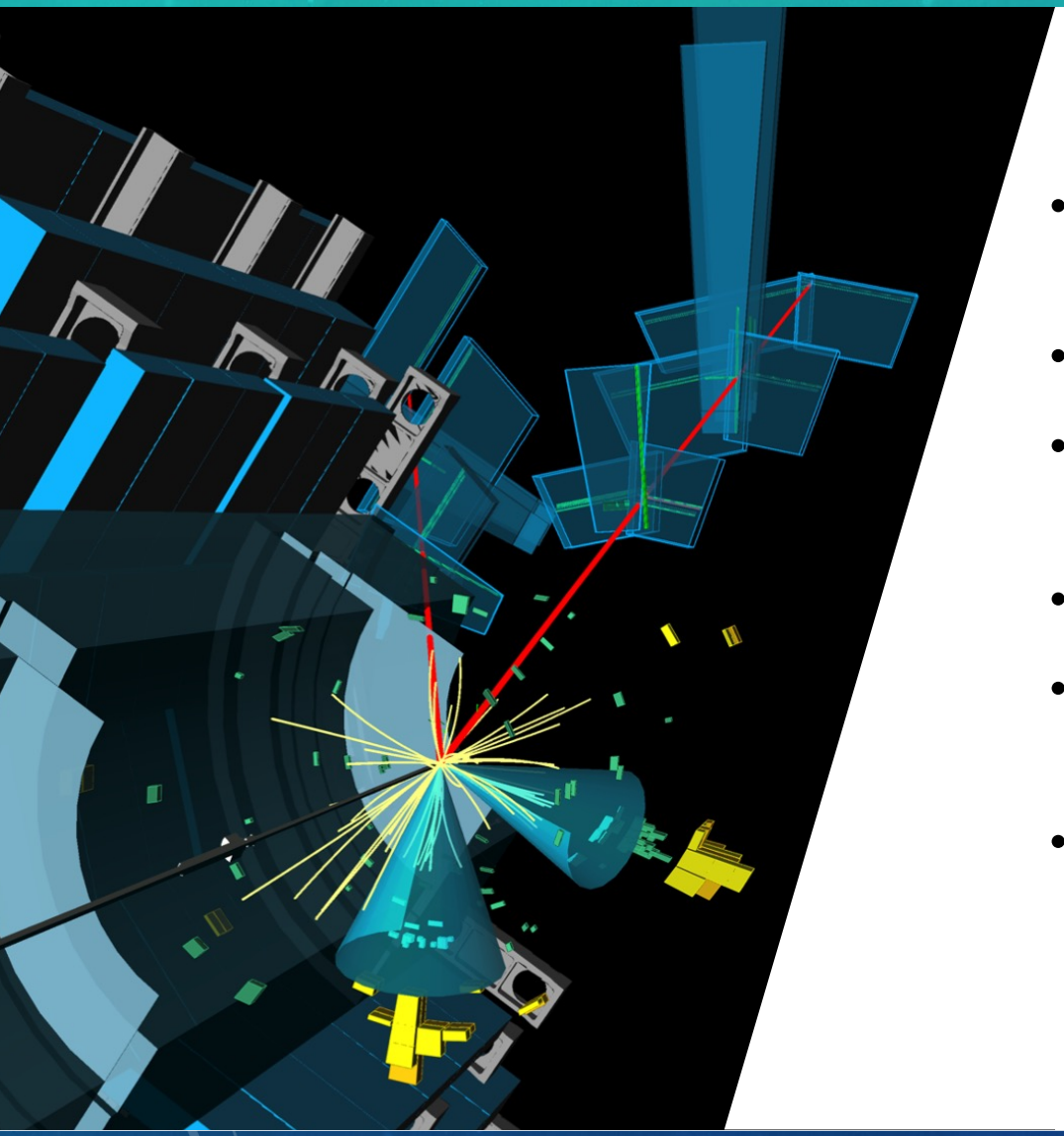
LPC Physics Forum - 23 February 2023

Introduction



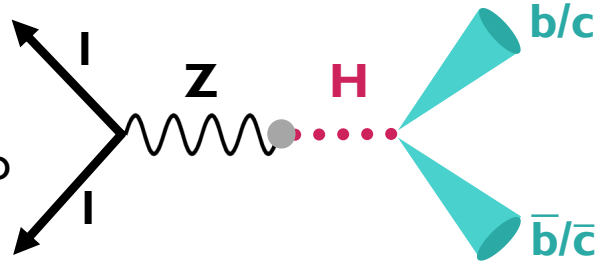
- Overview of the **VH, H → $b\bar{b}$** and **VH, H → $c\bar{c}$** analyses in ATLAS
- Targeting H→bb and H→cc decays in the VH production mode
- Categorisation into channels based on vector boson decay (Z→νν, W→lν, Z→ll)
- Identification of b- and c-jets with the use of jet flavour tagging
- Categorisation of events by p_T of of vector boson and jet multiplicity
- Fit to di-jet invariant mass or BDT distribution to extract signal strengths or cross-sections in the STXS scheme

Analysis Regimes

Two different topologies used based on transverse momentum of the Higgs boson (p_T^H):

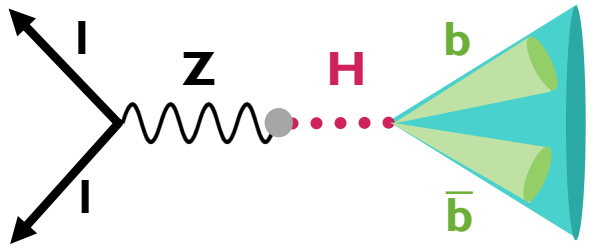
Resolved (low p_T^H)

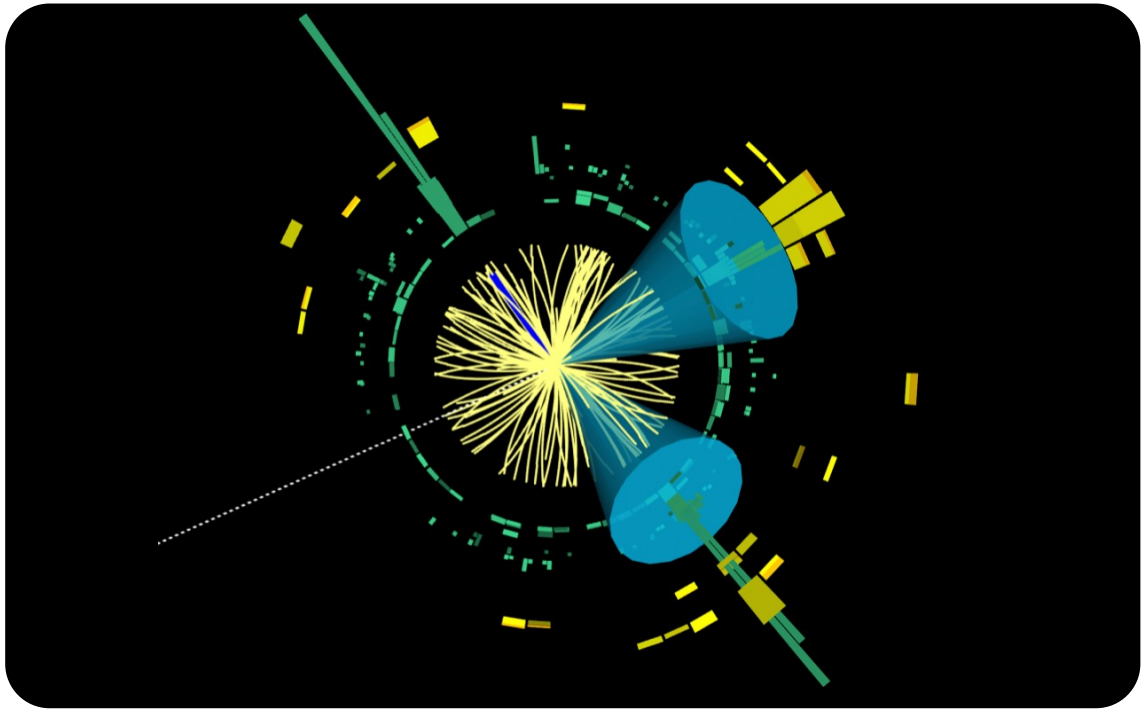
Higgs candidate reconstructed from two R=0.4 jets

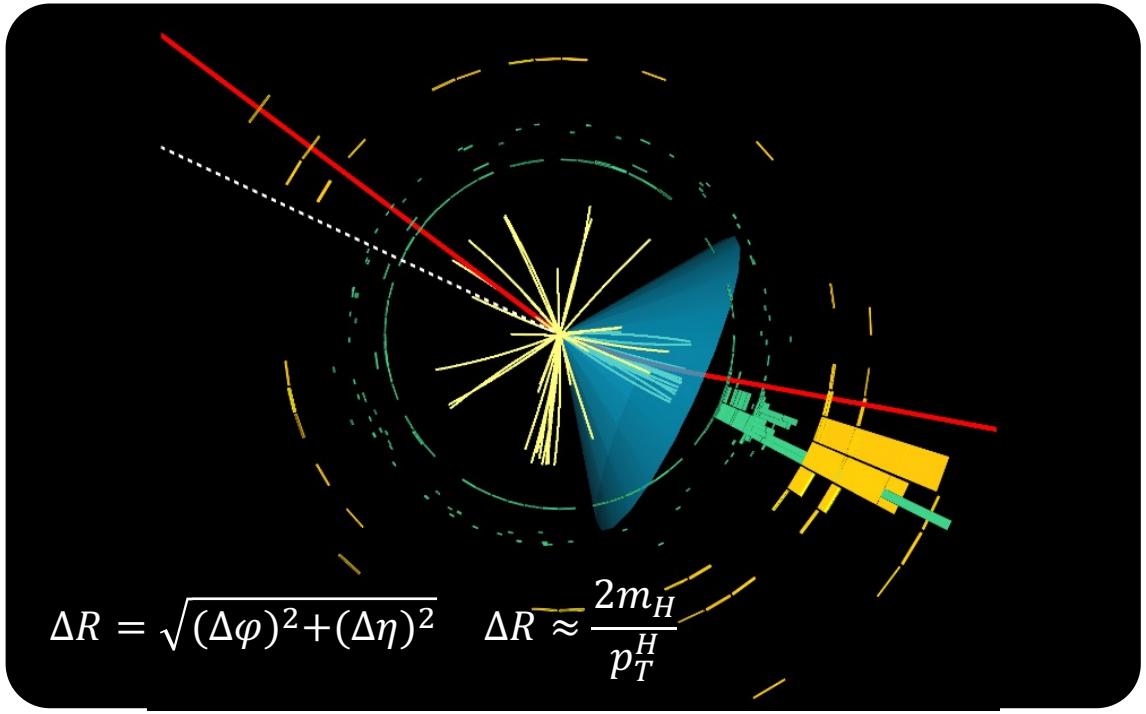


Boosted (high p_T^H)

Higgs candidate reconstructed one R=1.0 jets



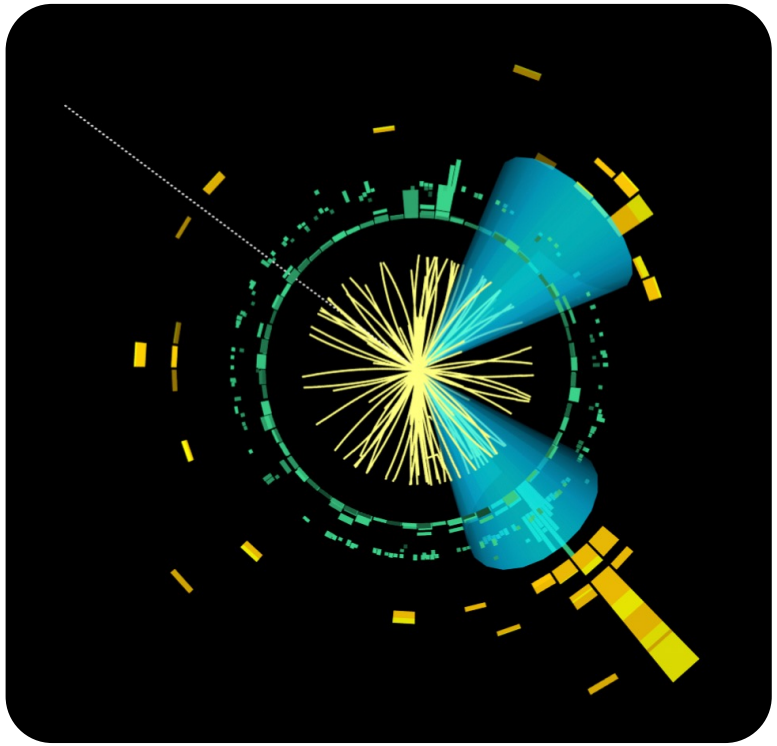


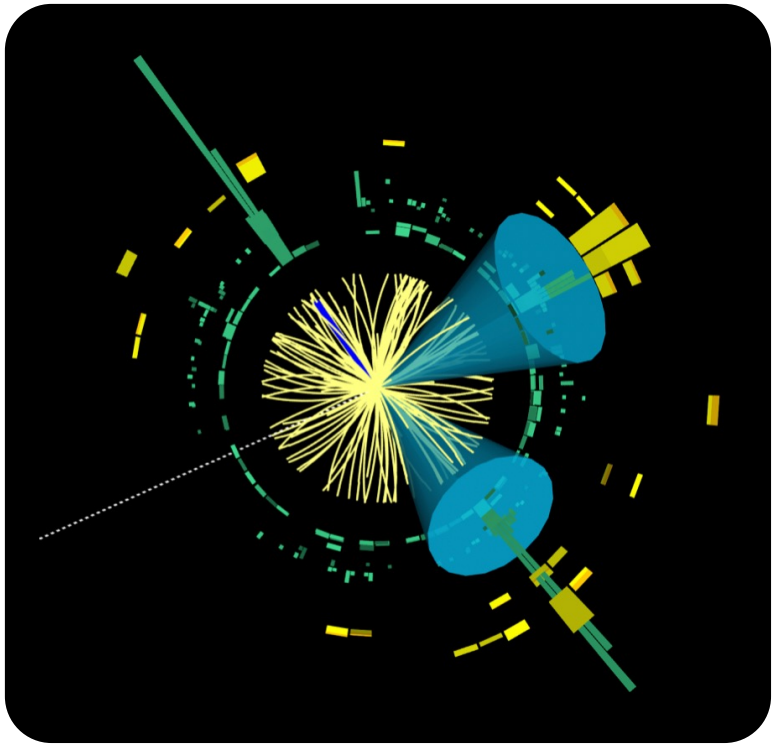


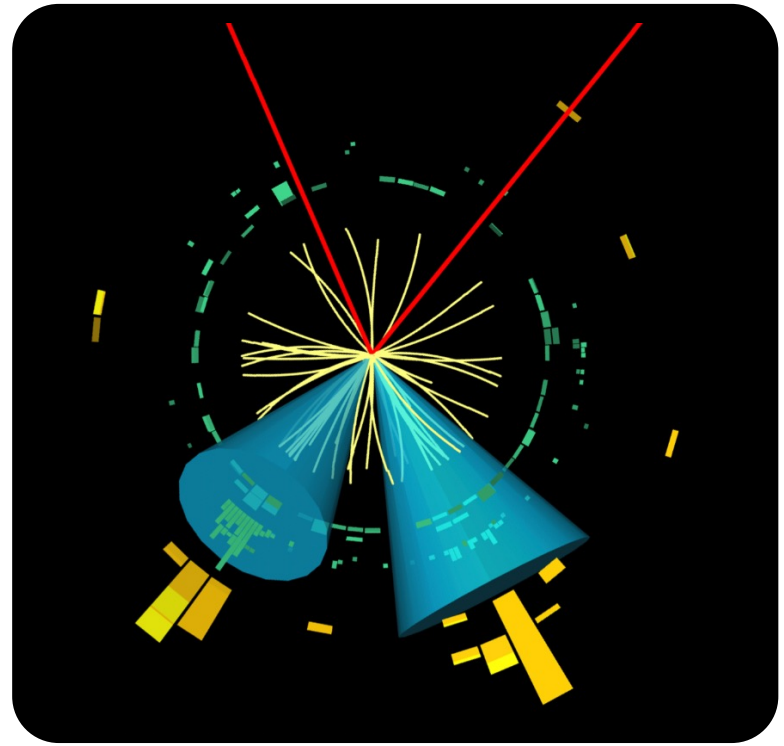
Analysis channels

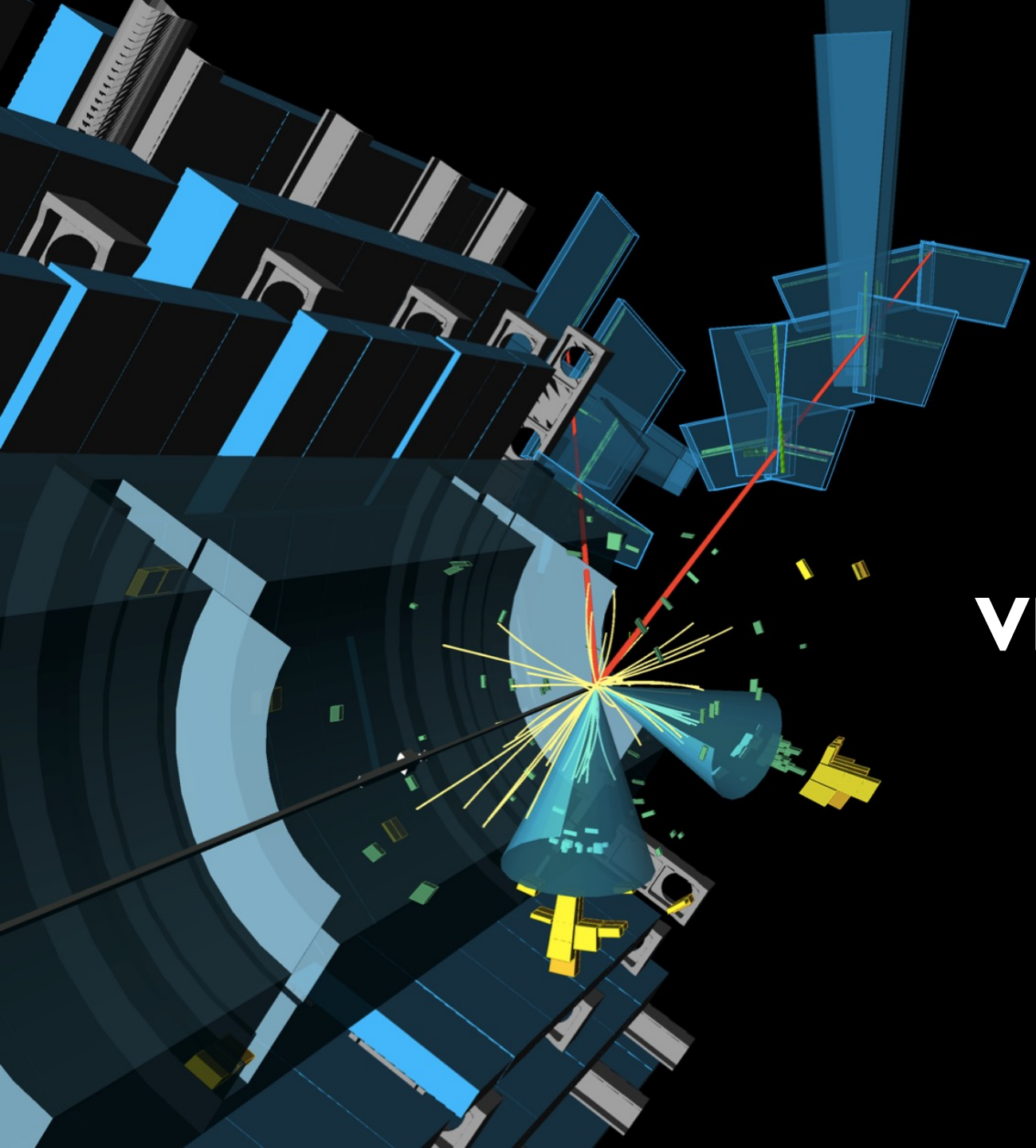
Categorisation of events into channels by the decay of the vector boson into leptons (electrons or muons)

0 lepton	***1 lepton***	***2 lepton***
2 b/c-tagged jets + MET	*2 b/c-tagged jets + lepton +MET*	*2 b/c-tagged jets + 2 leptons*









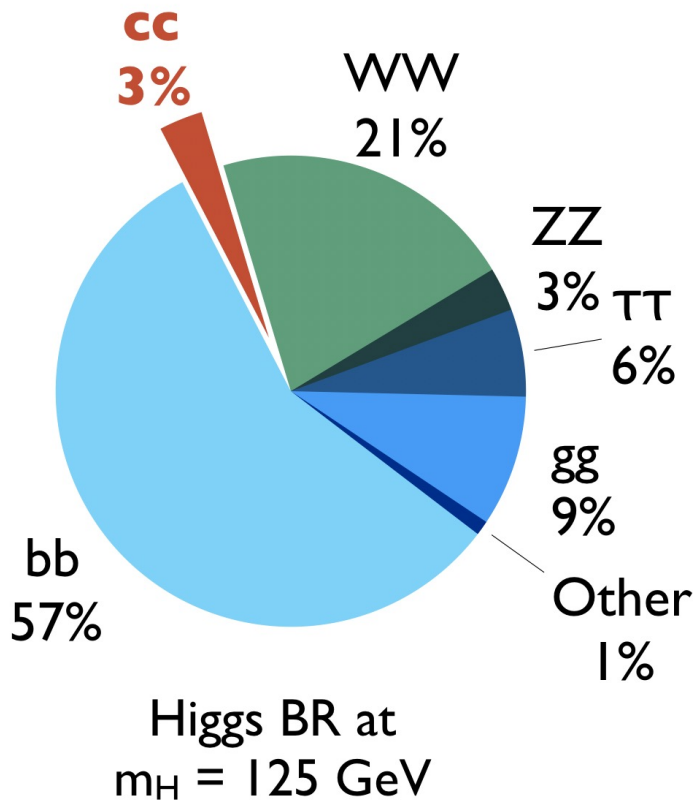
VH(→cc)

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



Higgs BR at
m_H = 125 GeV

Goal: Use the ATLAS Full Run 2 dataset (13 TeV) to improve on the limit on the VH(cc) process

- Second ATLAS H→cc search, extending the previous iteration by including the Full Run 2 dataset and additional channels

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

Analysis strategy

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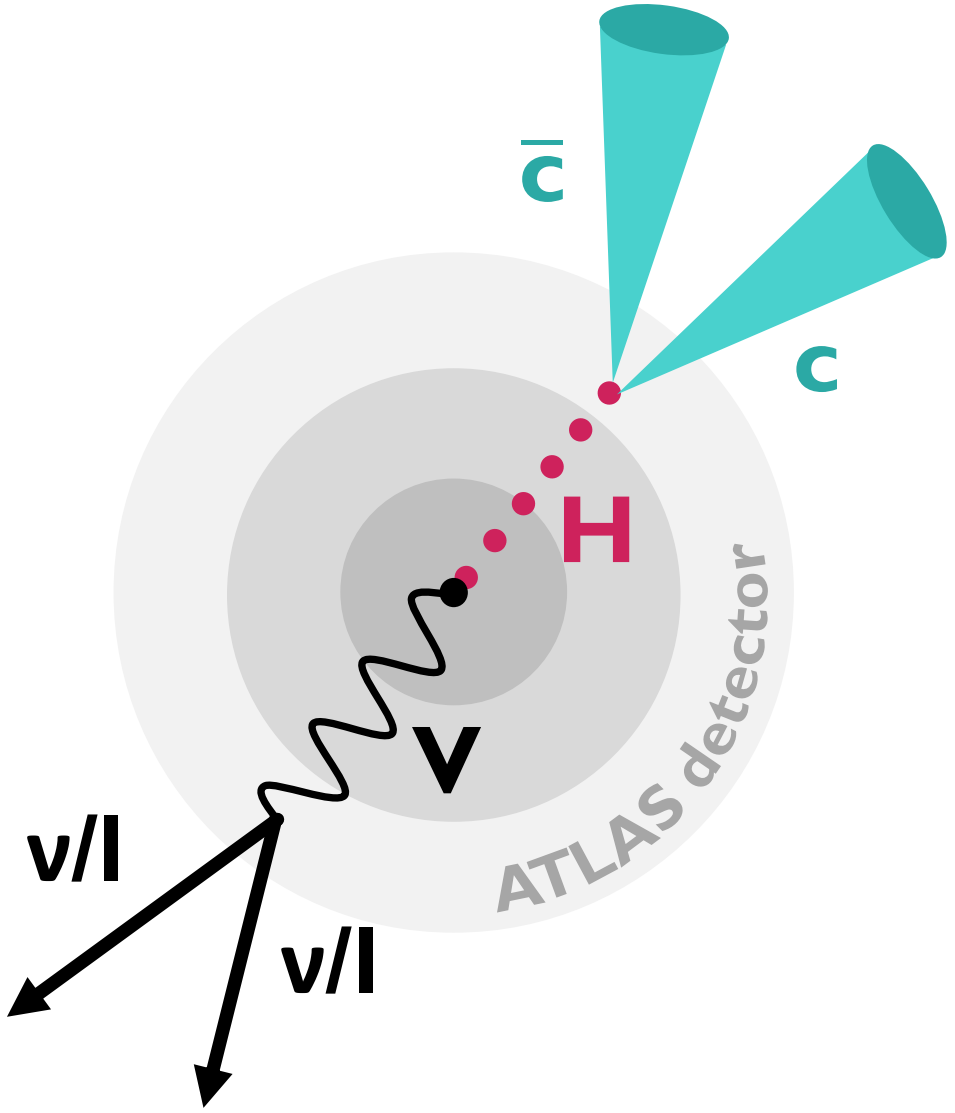
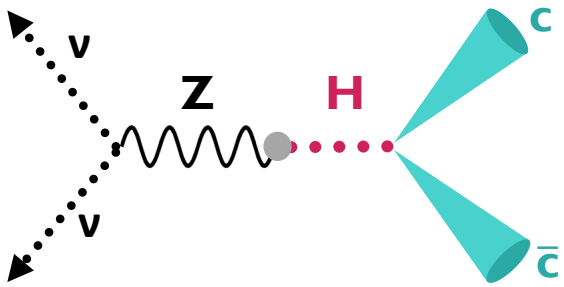
- Search in VH production to suppress QCD background
- Use leptonic decays of the W or Z boson
- Use flavour tagging to identify jets originating from charm-jets
- **Cross-check measurement of Diboson decays containing c-quarks**
- Three signals:
  - **VH, H → $c\bar{c}$**
  - **VZ, Z → $c\bar{c}$**
  - **VW, W → cq (q=d,s)**

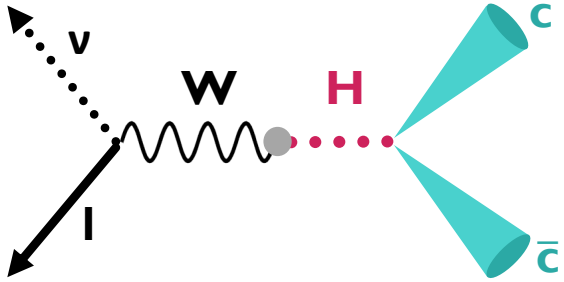


Analysis strategy

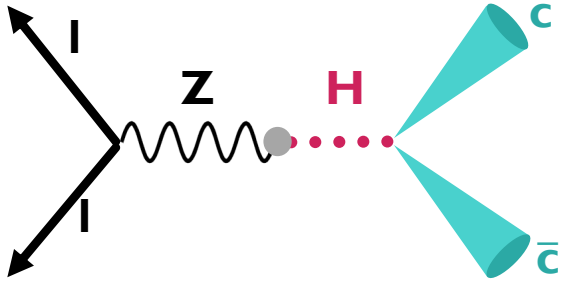
0 lepton



1 lepton



2 lepton



- Categorisation into channels by the decay of the vector boson
- Event categorisation in each channel:

	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

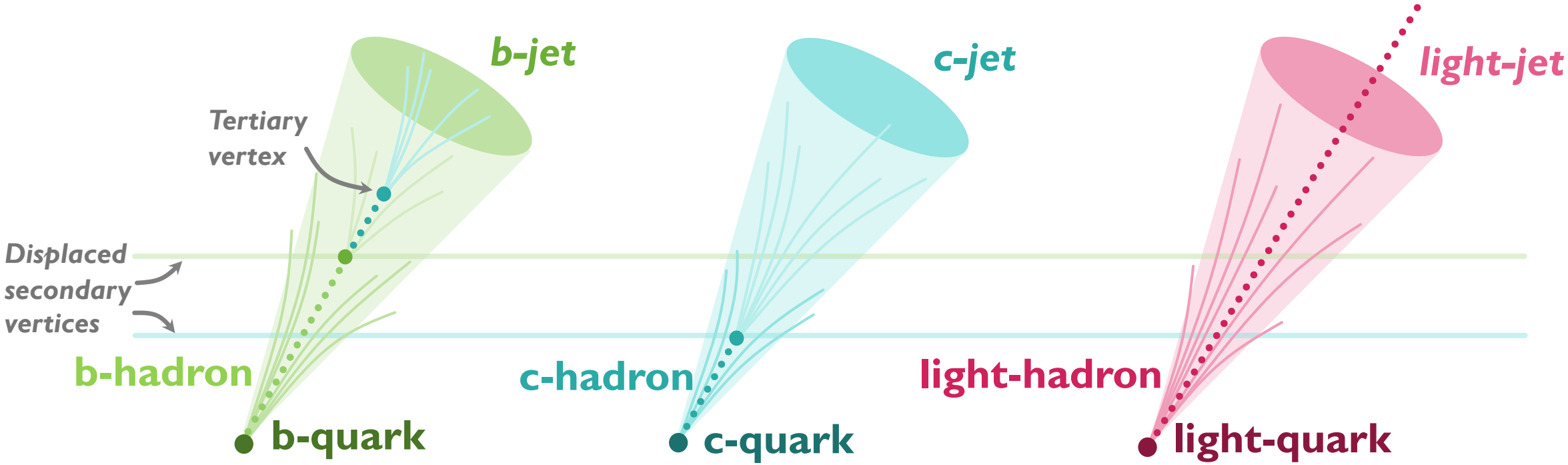
→ *pTV – transverse momentum of the vector boson*
(*) only in 2 lepton channel

- **Cut-based analysis:**
  - Backgrounds suppressed using optimised cuts (closely following VH(bb)[1] analysis)
  - m_{cc} of two leading p_T jets as a discriminant

[1] *Measurement of VH, H→bb decays: Eur. Phys. J. C 81 (2021) 178*

Flavour tagging

- Main challenge of the analysis: Identification of c-quarks as they hadronise in the ATLAS detector
- Mass and lifetime of c-hadrons between those of b-hadrons and signatures of light-jets



- Machine learning tools exploiting the lifetime and mass of heavy hadrons → **charm-tagging**

→ Utilise secondary and teritary vertices, impact parameters, jet substructure

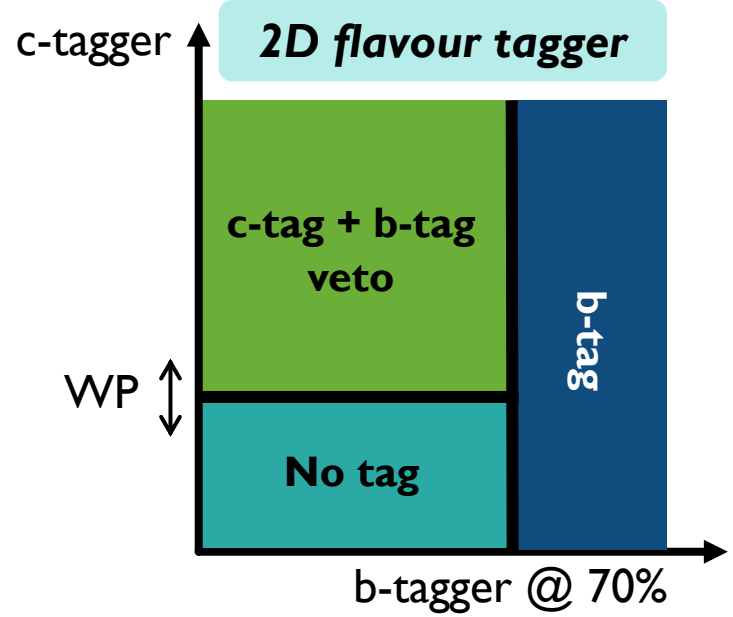
Flavour tagging in VH(cc)

- Goal: **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
  - Veto events with b-tags 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%)**

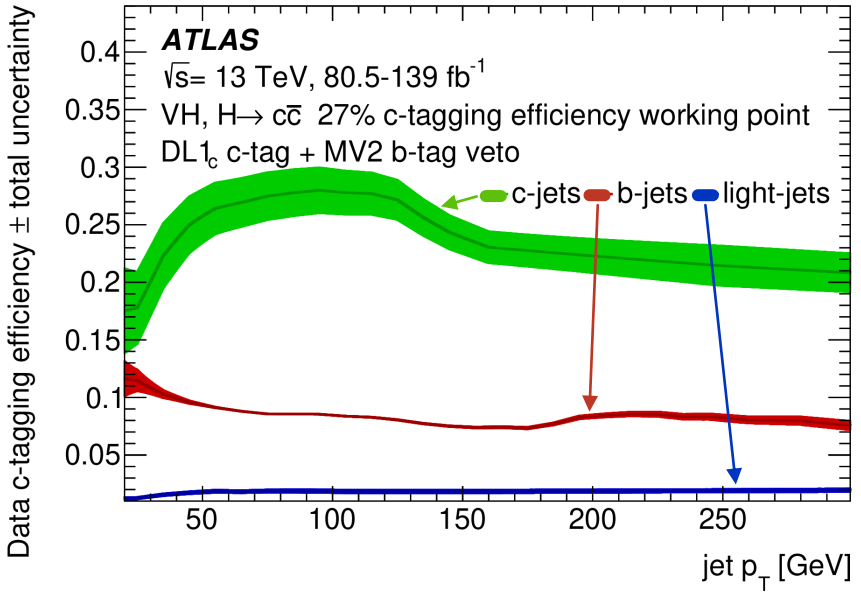
→ Used to define 1 and 2 c-tag regions

- Low c-tagging efficiency means low MC statistics

→ Mitigate by **truth-tagging** (weighing events by c-tagging probability, instead of applying direct discriminant)



Efficiency for the calibrated WP



Signal regions

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

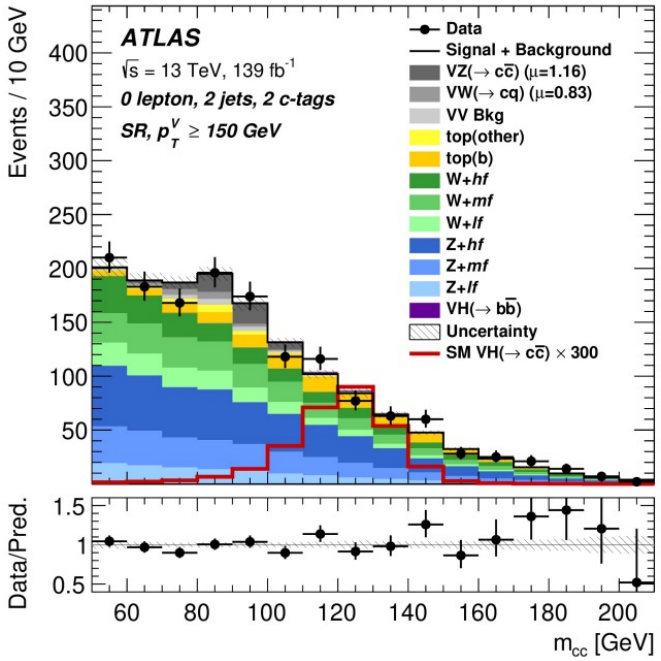
Signal: **VH(cc)**, **VZ(cc)**, **VW(cq)**

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

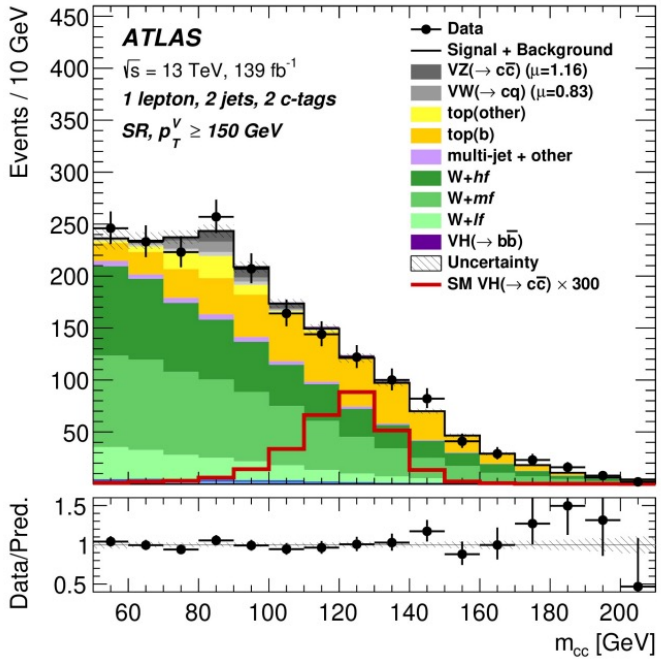
Subdominant backgrounds: **VH(bb)**, **VV background**

2 c-tag

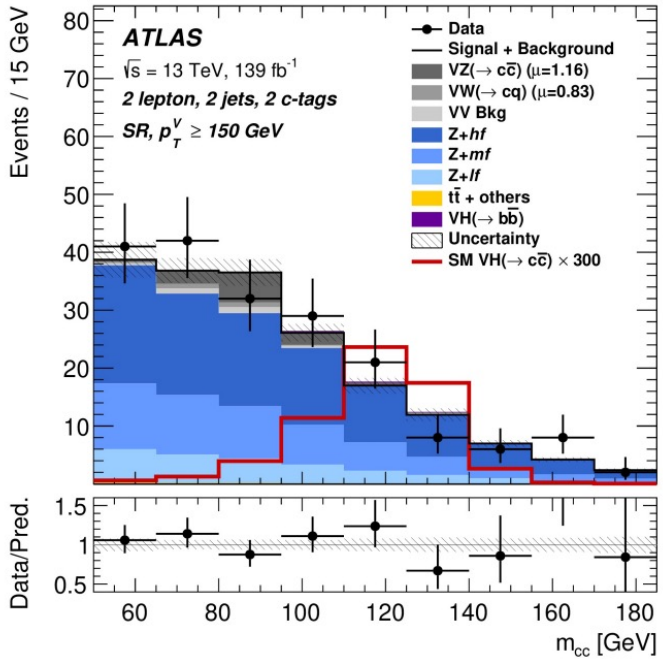
0 lepton



1 lepton



2 lepton

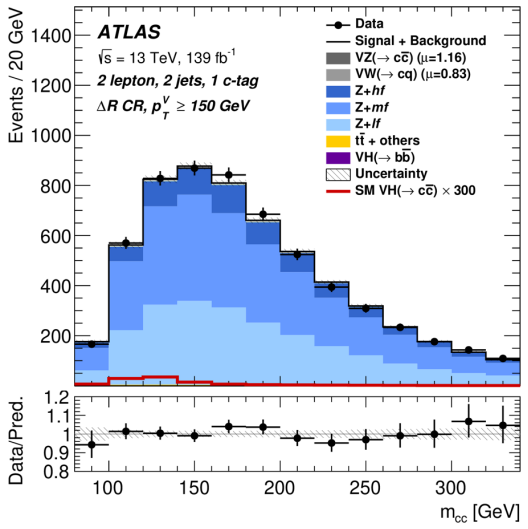


Control regions

- Excellent understanding of background necessary for an analysis with such small signal

→ **all major backgrounds constrained in dedicated control regions**

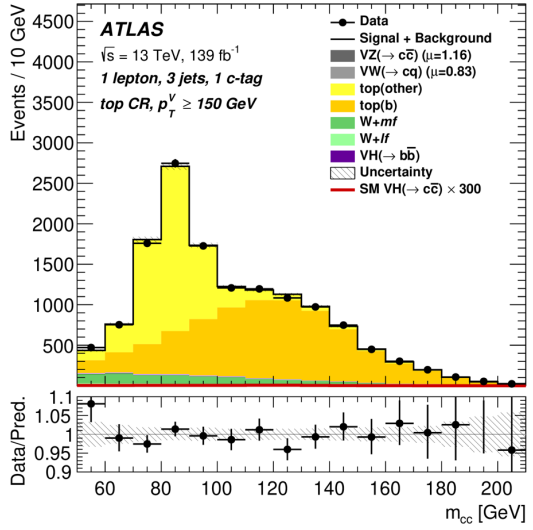
V+jets background



For each SR, define corresponding CR using event with high ΔR_{cc}

→ Constrain V+jets background containing heavy-flavour jets

Top background



Top CR in 0/1 lepton, constructed by requiring ≥ 1 b-tag

→ Constrain ttbar and single top backgrounds

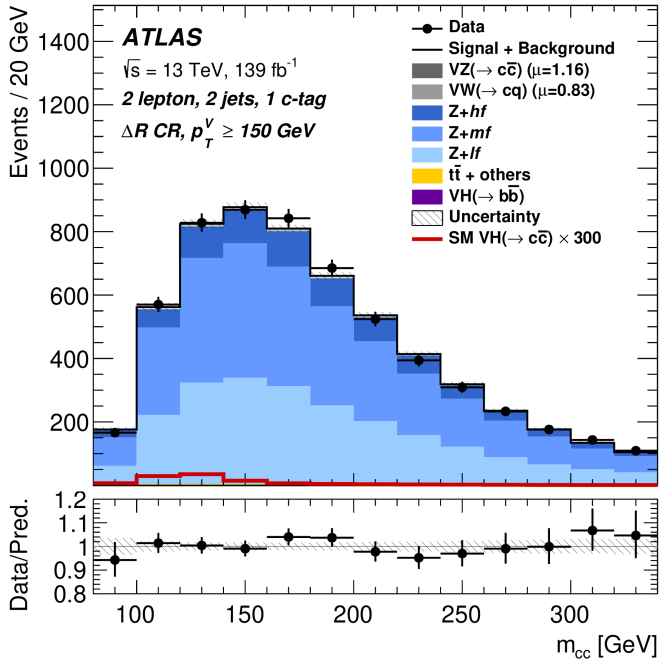
- And additional yield-only control regions for minor backgrounds (V+jets events with light-jets, ttbar in the 2-lepton channel)

V+jets modelling approach

- Start from **nominal simulated samples**
  - Nominally simulated with **Sherpa 2.2.1 5F MEPS@NLO** (NLO-accurate ME for up to 2 jets, LO-accurate ME for up to four jets)
  - Samples produced in slices of max(H_T, p_T^V) to control phase space sampling
  - Filters are applied to select events with heavy flavour jets
  - More details on generator setup here
- Constrain **normalisations** (and m_{cc} shapes) of V+jets in dedicated control regions, e.g. through selecting events with high ΔR between jets
- Float normalisations based on di-jet flavour:
  - VH(bb): Float V+hf (bb,bc,bl,cc) separately and take remaining components as predicted by simulation + uncertainty
  - VH(cc): Float separately V+hf (bb,cc), V+mf (bc,bl,cl) and V+l

  → In both cases, with uncertainties applied on flavour composition
- Determine floating normalisations with as much granularity as data allows (in different bins of jet multiplicity, p_T of vector boson)

Example of V+jets control region in VH(cc)



V+jets modelling approach

- Derive uncertainties by considering different variations
  - **MadGraph+Pythia8 5F MEPS@LO** (up to 4 partons) → dominant uncertainty
  - Renormalisation/factorisation scale (μ_R, μ_F) variations
- Calculate shape and normalisation effects of each alternative generator
- Group normalisation effects together, to calculate:
  - **Overall normalisation** uncertainties on smaller V+jets components
  - **Extrapolation uncertainties** between different analysis regions and on the **flavour composition** of backgrounds
  - **Shape uncertainties:** Consider also variations on the shapes of kinematic distributions based on the alternative samples, and include shape uncertainties in the analysis

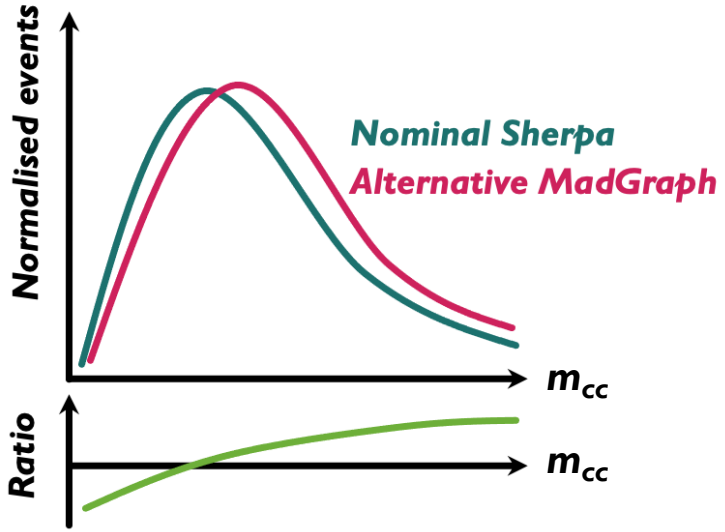
  → directly parametrise the ratio of nominal and alternative generators on m_{cc}

Extrapolation uncertainties calculated from yields n_1 and n_2 from regions 1 and 2 (e.g. SR and CR):

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

Different sources added in quadrature

Illustration of shape systematics for mass-based fit



Statistical analysis

- **Simultaneous binned likelihood** fit to m_{CC} distributions of the 16 SR and 28 CR

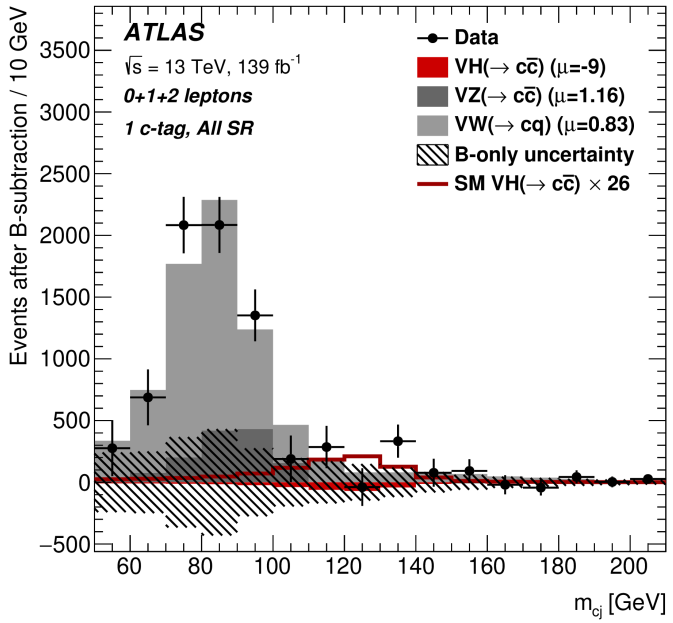
$$\mathcal{L}(\mu, \vec{\theta}, \vec{\gamma}) = \prod_{i \in \text{bins}} \text{Pois}(N_i | \mu s_i(\vec{\theta}) + \gamma_i b_i(\vec{\theta})) \times \prod_{\theta \in \vec{\theta}} \frac{1}{\sqrt{2\pi}} e^{-\theta^2/2} \times \prod_{i \in \text{bins}} \text{Gauss}(\beta_i | \gamma_i \beta_i, \sqrt{\gamma_i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

Poissonian likelihood | **Constraints on NPs** | **Constraints on MC stats.**

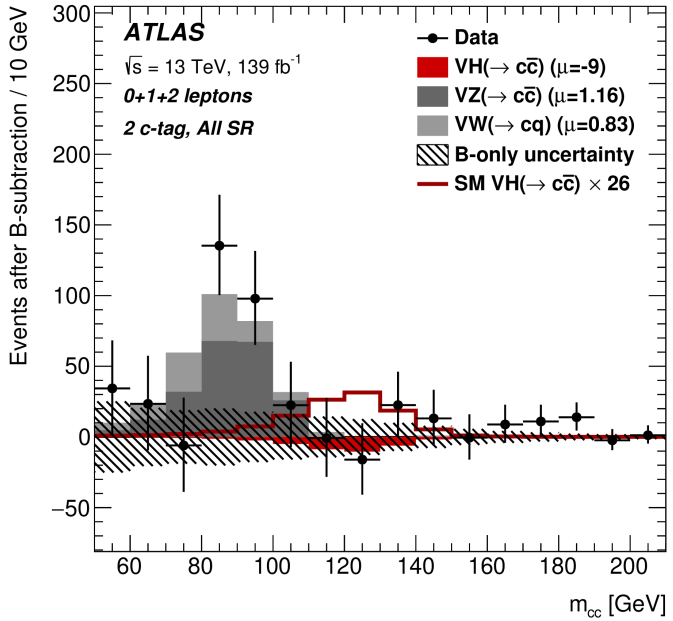
- Simultaneous 3POI fit to signal strengths μ of: **VH(cc),** **VZ(cc),** **VW(cl)**
- **Systematic uncertainties** as nuisance parameters:
  - Experimental uncertainties (flavour tagging, jets, MET and lepton)
  - Floating normalisations of the of the major backgrounds (constrained in control regions)
  - Theory and modelling uncertainties (e.g. from comparing alternative simulated samples)
  - Uncertainties on statistics of simulated samples

Mass distributions

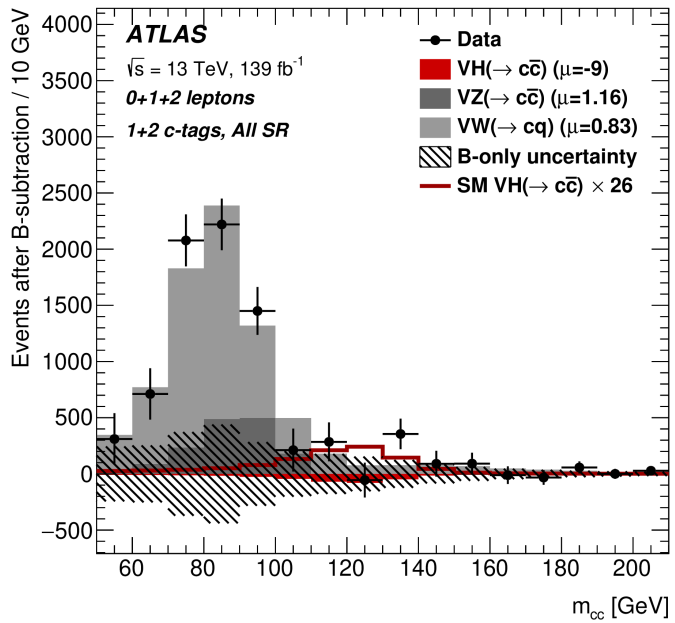
1 c-tag



2 c-tag



1+2 c-tag

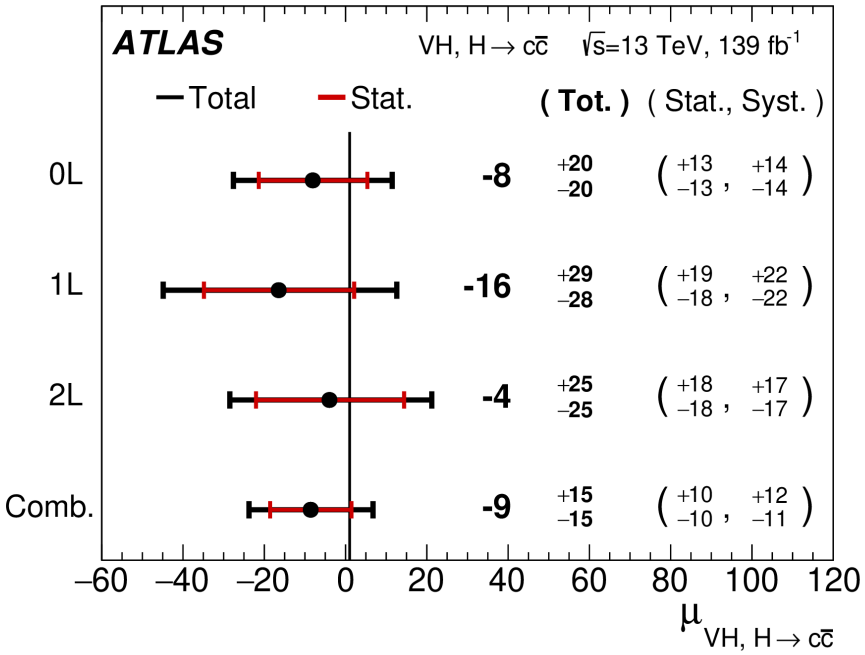


- m_{cc} distributions with backgrounds subtracted → good agreement of data and simulation
- Measurement of the **VW(cq)** and **VZ(cc)** Diboson processes:
  - **VW(cq)** significance of **3.8σ** (4.6σ expected)
  - **VZ(cc)** significance of **2.6σ** (2.2σ expected)

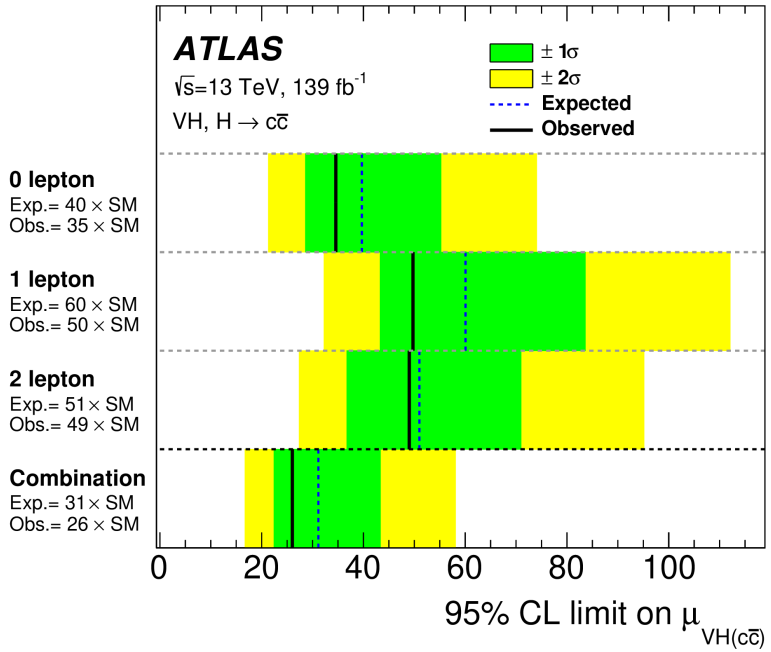
→ **First measurements of VZ(cc) and VW(cq) using c-tagging!**

Signal strengths and limits

Best fit signal strength for VH(cc)



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



- Best fit signal strength $\mu_{VH(cc)} = -9 \pm 15$ → compatibility with SM: 83.9%
  - Statistical and systematic uncertainties of similar size
  - Leading systematic uncertainties: Modelling V+jets/top processes and flavour tagging
- Observed VH(cc) limit of **26 x SM** (31 x SM expected) → **significant improvement on previous iteration**

κ_c interpretation

- Use this analysis to directly probe Higgs-charm coupling y_c
- Use κ-framework for the interpretation

→ Introduce coupling strength modifiers, e.g. $\kappa_c = y_c / y_c^{SM}$

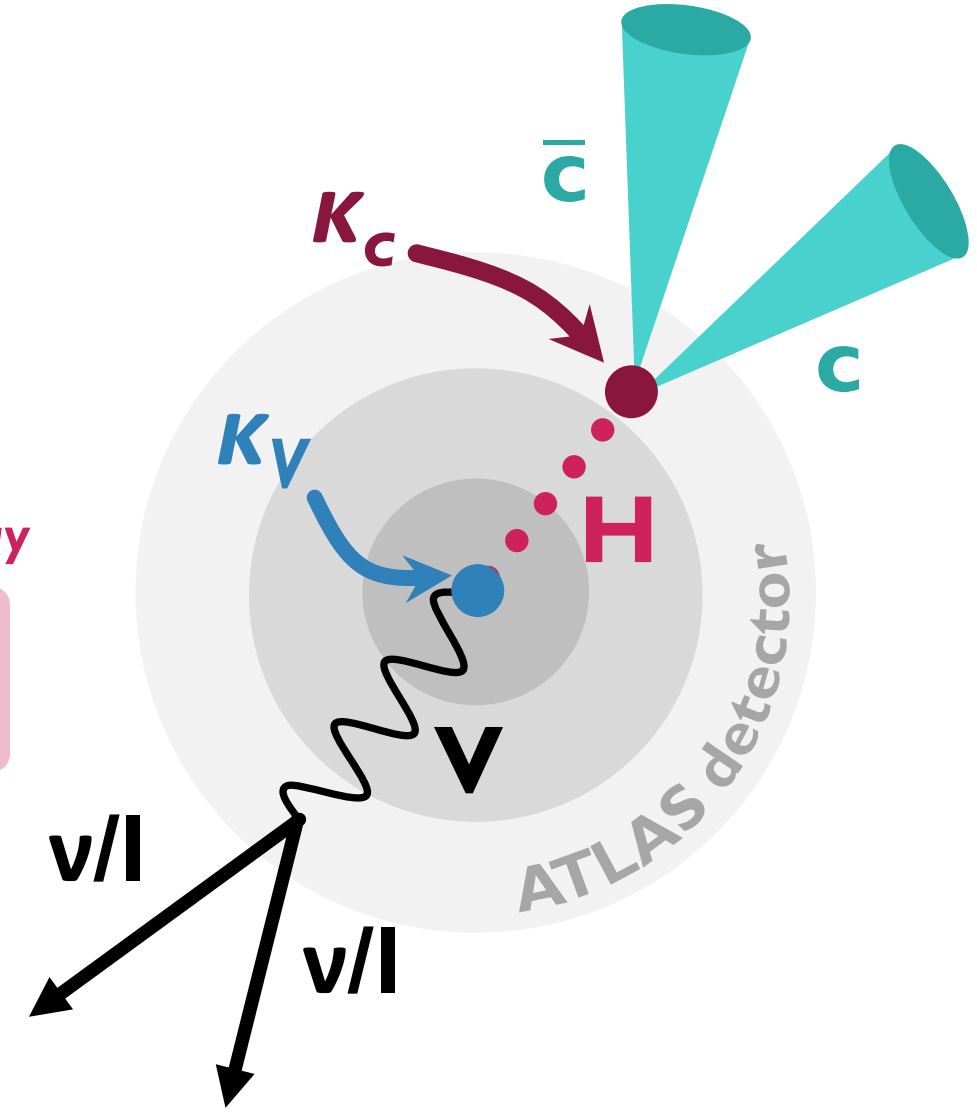
→ **Deviation of Higgs coupling from SM expectation**

- Possible modifications in the VH(cc) case:

$$\sigma \times BR\left(VH(\rightarrow c\bar{c})\right) = \sigma_{SM} \times BR\left(VH(\rightarrow c\bar{c})\right)_{SM} \underbrace{\kappa_V^2}_{\text{production}} \times \underbrace{\frac{\kappa_c^2}{\kappa_H^2}}_{\text{decay}}$$

- Modifications to the total Higgs width:

$$\kappa_H^2 \sim 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 + \cdots + BSM\ decays$$



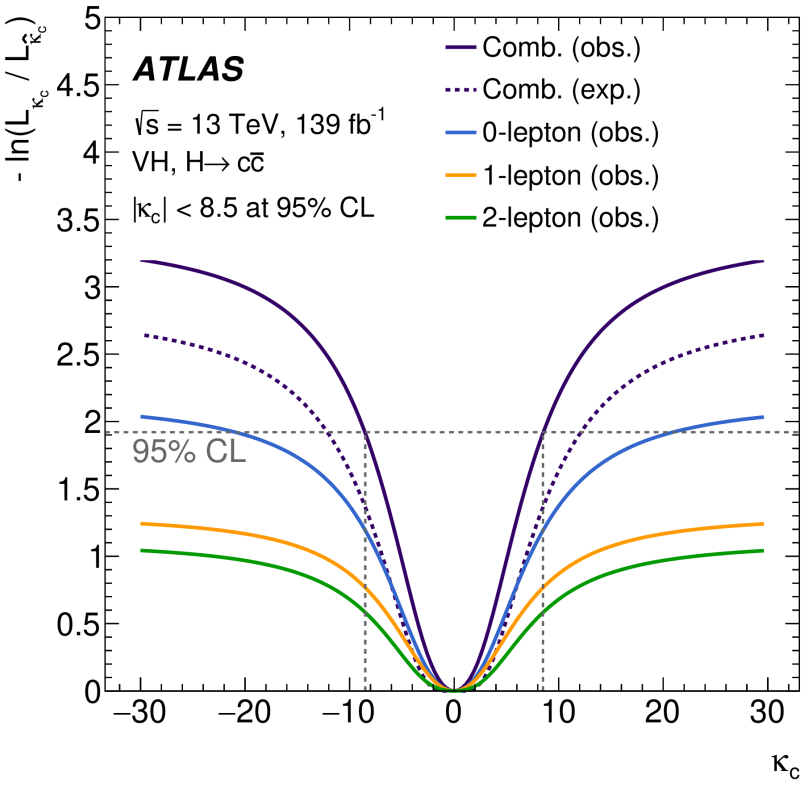
κ_c interpretation

- **Consider modifications to decay only, i.e. only κ_c**
- Set all other coupling modifiers to 1
- Assume no contribution from BSM decays to total Higgs width
- **Signal strength parameterised as:**

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

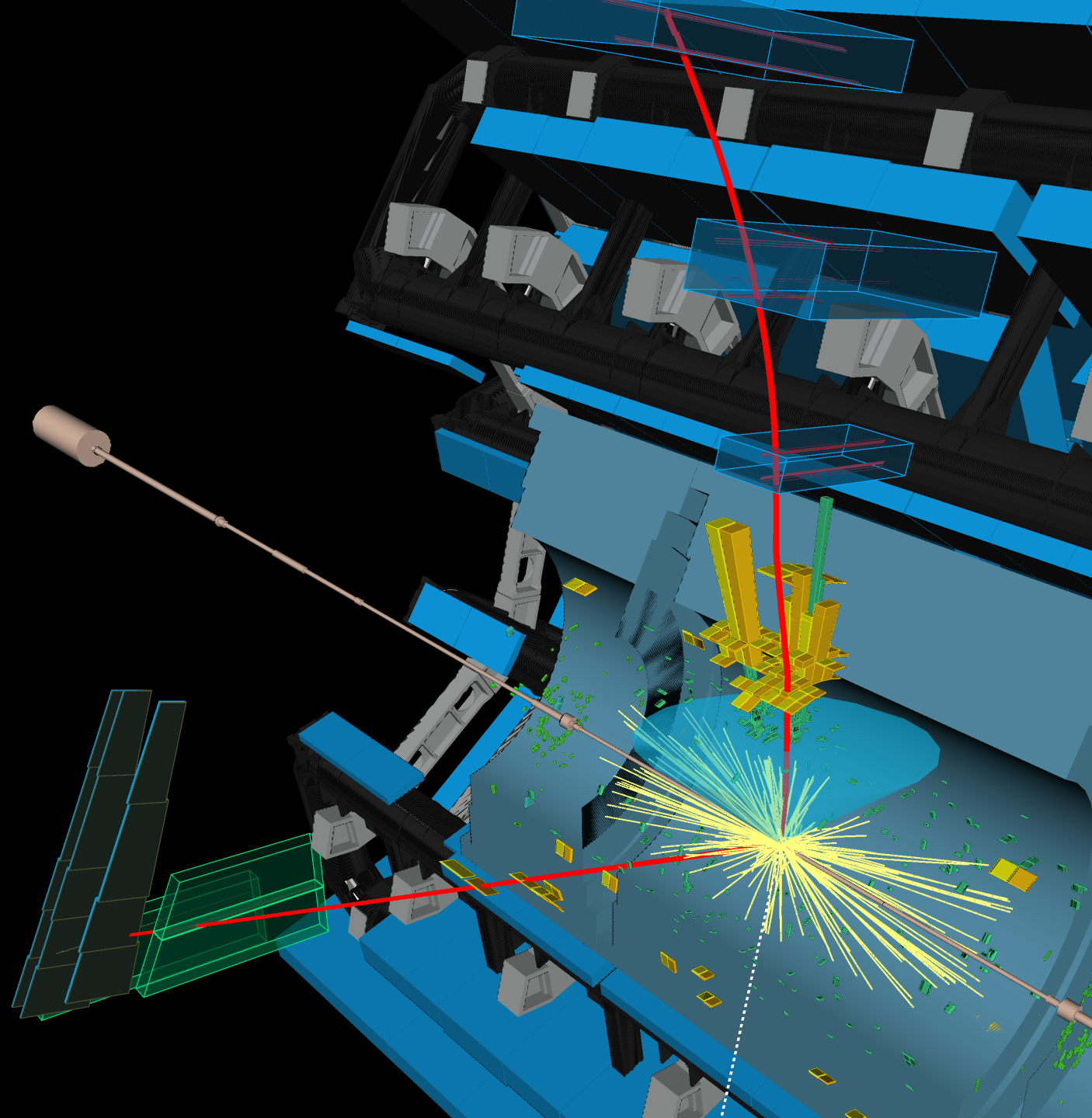
- In this parametrisation we are only sensitive to κ_c if limit on $\mu<35$
- Expected limit on κ_c at 95% CL in combined fit $|\kappa_c| < 12.4$
- Observed best fit $\kappa_c = 0$
- **Observed $|\kappa_c| < 8.5$ @ 95%CL**

Likelihood scan of κ_c



Resolved and boosted

VH(→bb)



VH(→bb) resolved strategy

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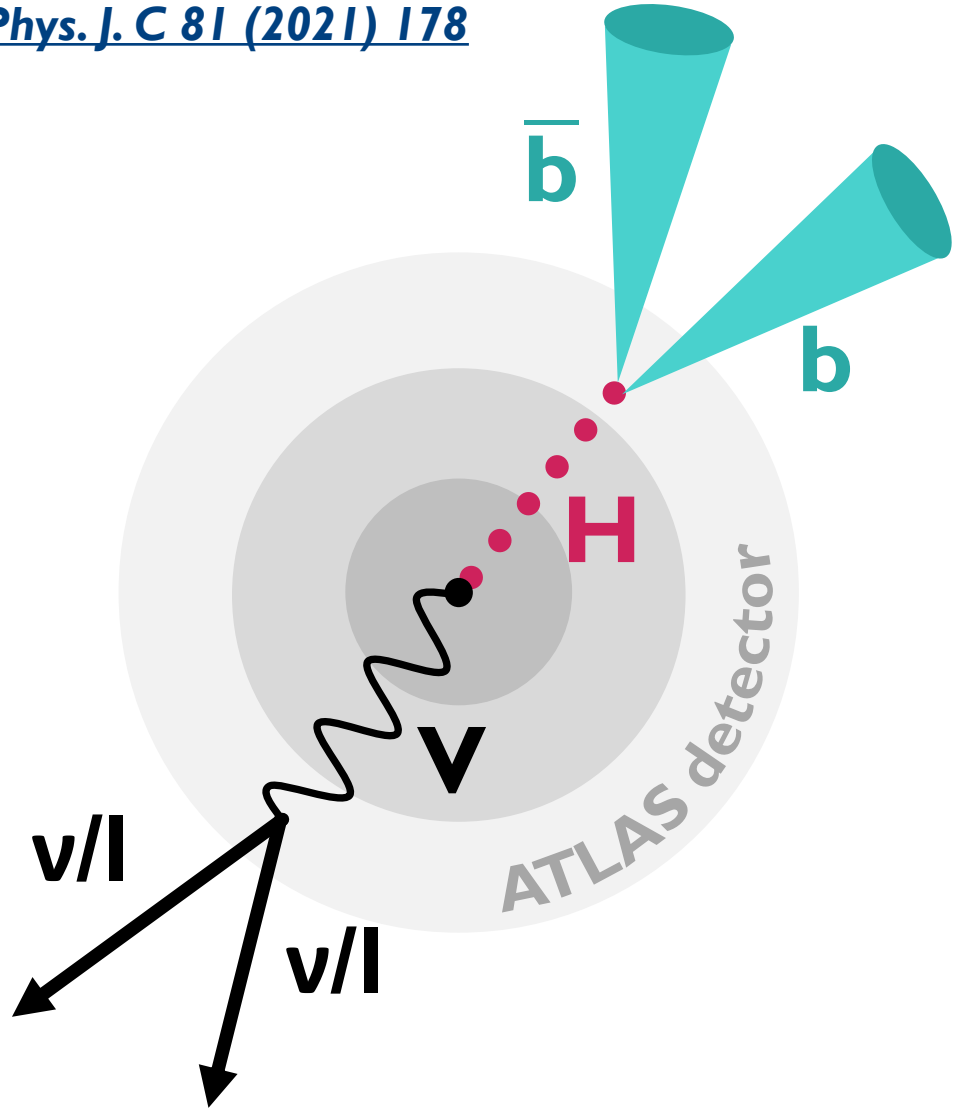
- **Measurement of V(→leptons)H(→bb) decays**
- Selection:
  - Very similar to VH(cc) selection → 2 small-radius R=0.4 b-tagged jets
  - B-tagging using 70% working point using BDT-based tagger
  - Also perform diboson cross-check, measuring VZ decays
- Categorisation into 42 regions, based on:
  - 0,1,2 charged leptons → 3 channels
  - 0, 1 additional non b-tagged jets → 2-jet, 3-jet categeories
  - Bins of transverse momentum pTV

    →[75,150] (2-lepton), [150,250], >250 GeV
  - Signal and control regions defined in $\Delta R(b_1,b_2)$-p_T^V plane → constrain V+jets from events with high ΔR



VH(→bb) resolved strategy

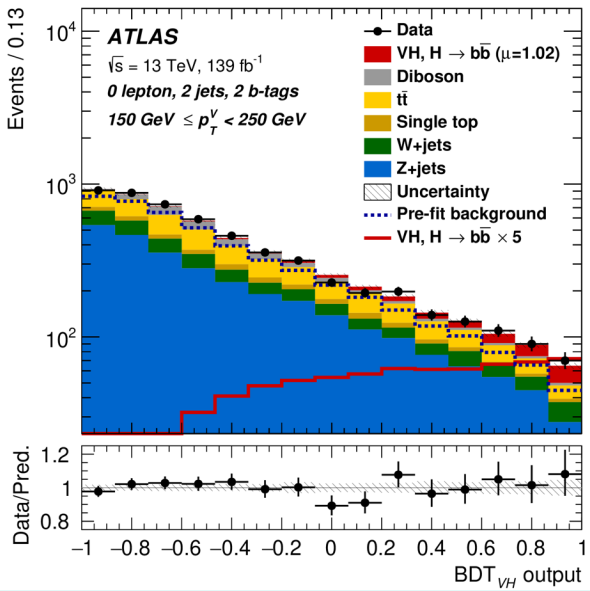
- **Background modelling** from simulation
  - Except data-driven estimate for QCD multi-jet in 1-lepton and ttbar in 2-lepton
  - Main backgrounds: **V+jets and ttbar** → normalisations of main backgrounds determined from dedicated control regions
  - Modelling uncertainties (shape and normalisations) largely assessed from generator comparisons (and some data-driven estimates)
- **Multivariate discriminant** used in signal regions

→ trained to distinguish VH(bb) from background using kinematic variables and flavour tagging information

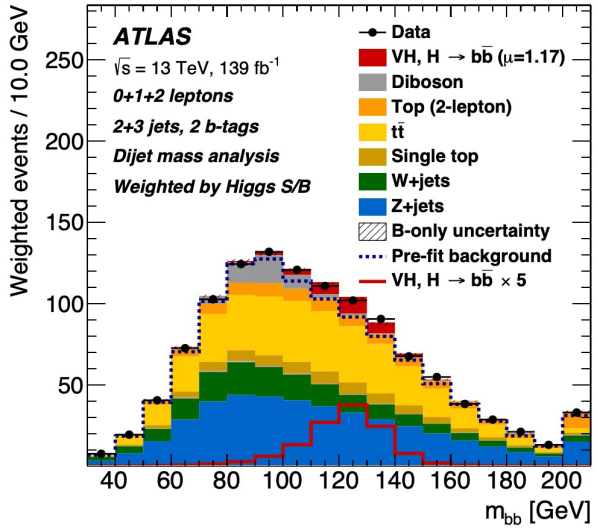
- Statistical analysis with **binned profile likelihood fit using BDT score** in the signal regions, and yields only in the control regions

→ Extract signal strength and cross-section in the STXS scheme

Fitted BDT discriminant

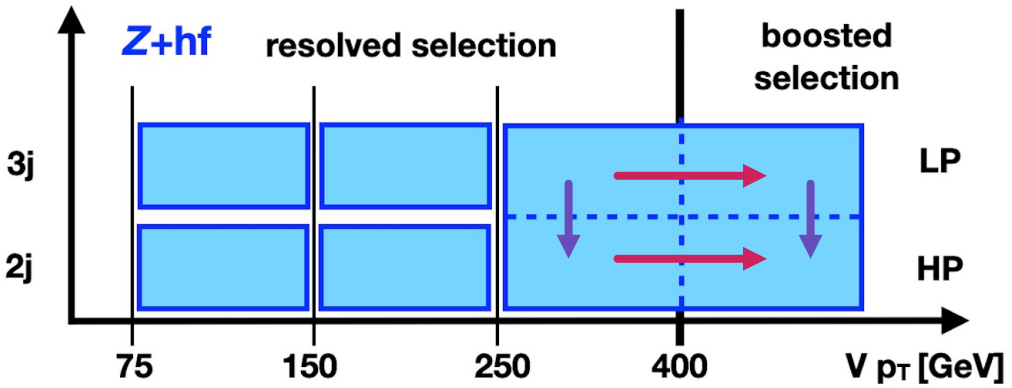


Summed m_{BB} distribution



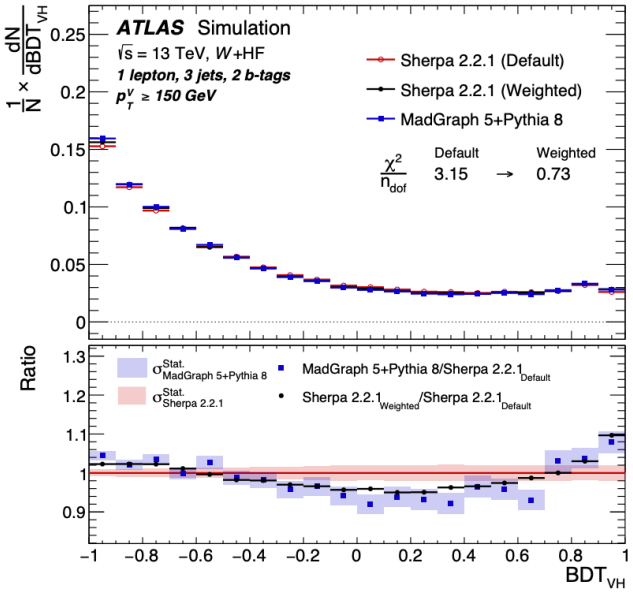
V+jets modelling approach

*Example of floating normalisation scheme in VH(bb) → p_T^V and **jet multiplicity** acceptance uncertainties are highlighted*

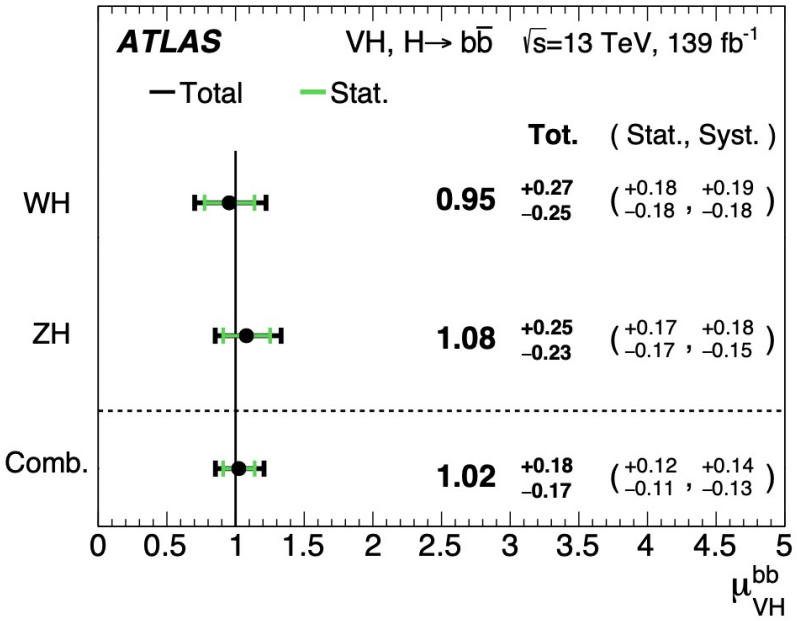


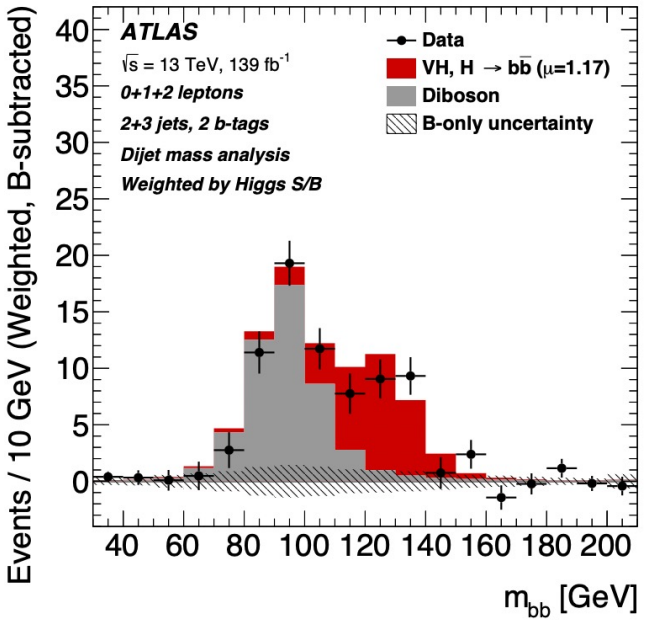
- Similar approach as in VH(cc):
- Use **Sherpa 2.2.1 5F MEPS@NLO** as nominal samples
- Assess systematics from:
  - **MadGraph+Pythia8 5F MEPS@LO** → dominant uncertainty
  - Renormalisation/factorisation scale (μ_R, μ_F) variations
  - CKKW and matching scale variation in Sherpa 2.2.1 sample → small effect with limited statistics
- Determine overall normalisation uncertainties in control regions
- Derive modelling uncertainties:
  - **Extrapolation uncertainties** between different analysis regions and on the **flavour composition** of backgrounds
  - **W+jets shape uncertainties:** Use **BDT_R** technique → parametrise shape effect on multiple kinematic variables using BDT
  - **Z+jets shape uncertainties:** Instead of using MadGraph as alternative samples, use **data-driven estimation** of shape systematic from sideband data

Illustration of shape systematics for BDT-based fit



VH(→bb) resolved results





- **VZ cross-check** shows good agreement with SM $\mu_{VZ}^{bb} = 0.93^{+0.16}_{-0.13} = 0.93\ ^{+0.07}_{-0.06}(stat)\ ^{+0.07}_{-0.06}(syst)$
- Inclusive VH(bb) measured at **6.7 (6.7) obs. (exp.)** standard deviations and $\mu_{VH}^{bb} = 1.02^{+0.18}_{-0.17} = 0.93\ ^{+0.12}_{-0.11}(stat)\ ^{+0.14}_{-0.13}(syst)$
  - Observation of ZH(bb) at 5.3 (5.1)σ obs. (exp)
  - Strong evidence of WH(bb) at 4.0 (4.1)σ obs (exp)

→ Leading uncertainties from signal modelling, V+jets background modelling and flavour tagging

- STXS measurement also provided, discussed later

VH(→bb) boosted

- High p_T version of the VH(bb) resolved analysis
- Motivation: **New physics scenarios often predict deviation from SM at high momentum**
- Selection:
  - Higgs boson candidate defined from **large-radius jets**
  - Plus **2 associated b-tagged variable-radius jets** (reconstructed from charged-particle tracks, with radius varying with p_T)
  - Track-jets are b-tagged using multivariate algorithm with a 70% working point (w/ c- and light-jet reception of 9 and 304 respectively)
- Categorisation into 10 signal regions and 4 control regions:
  - Lepton channels: 0/1/2-lepton
  - Transverse momentum of vector boson: 250 < pTV < 400 GeV and pTV > 400 GeV
  - 0/1-lepton: Further categorisation based on number additional jets in the event (high/low purity signal regions)

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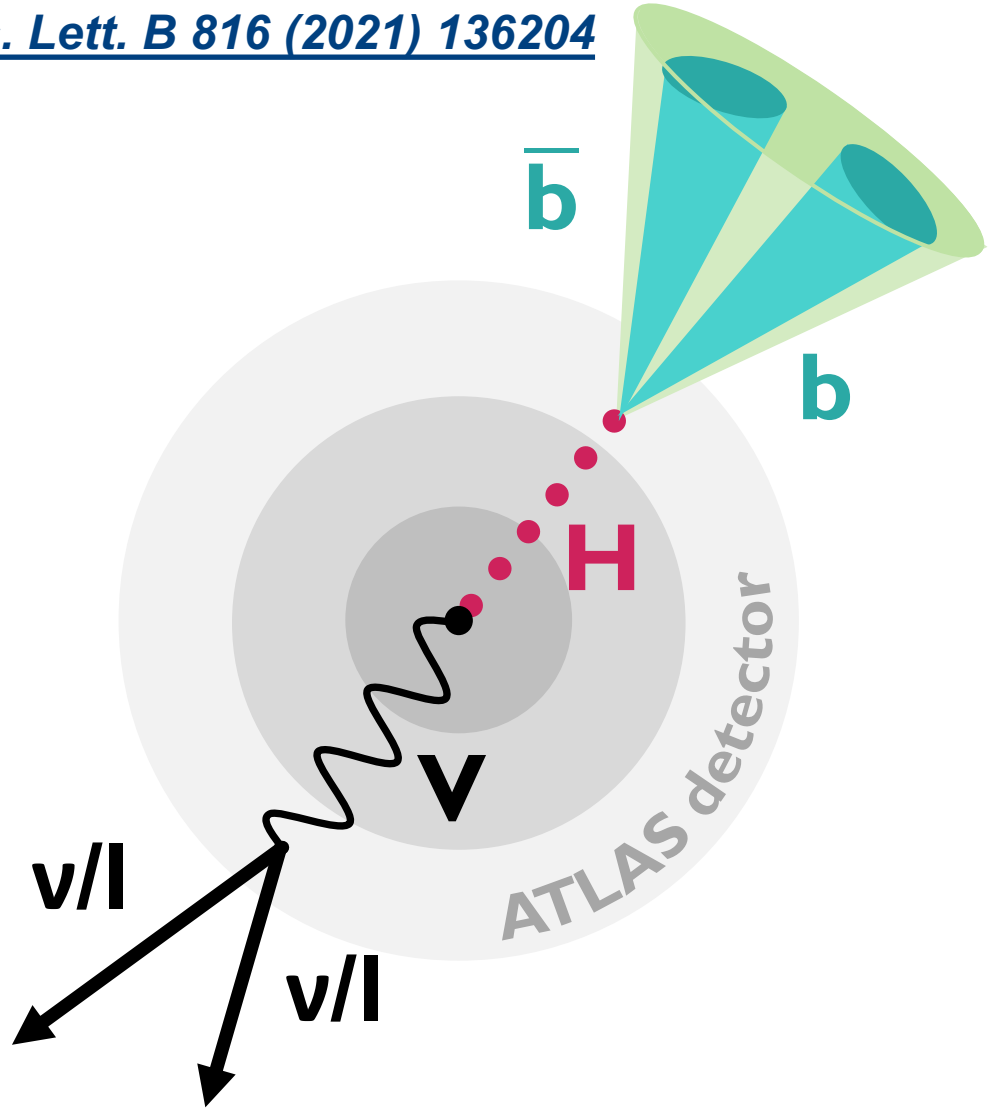
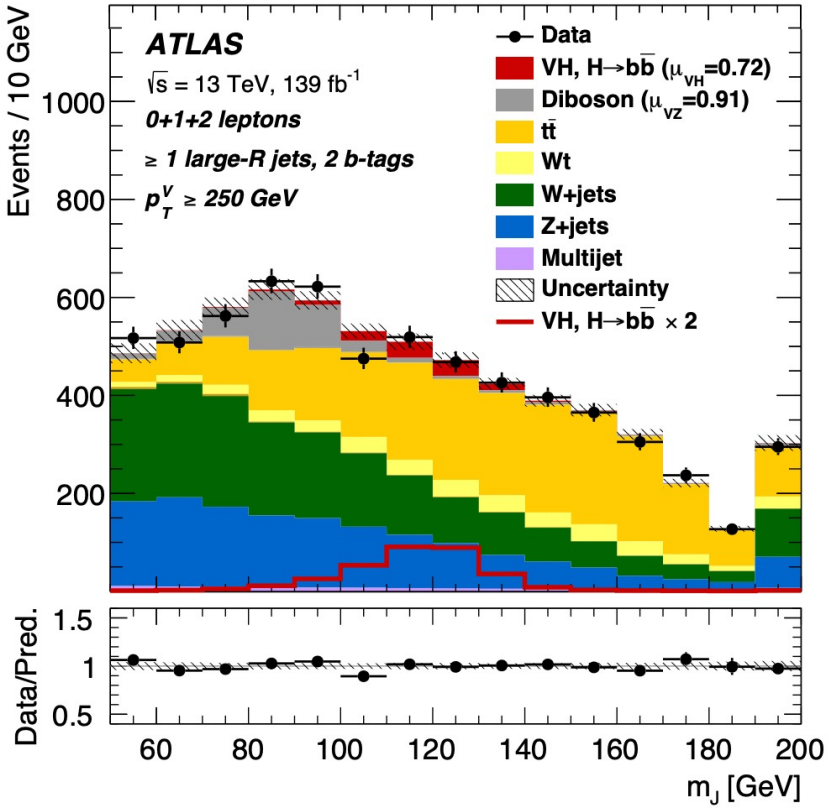


VH(→bb) boosted

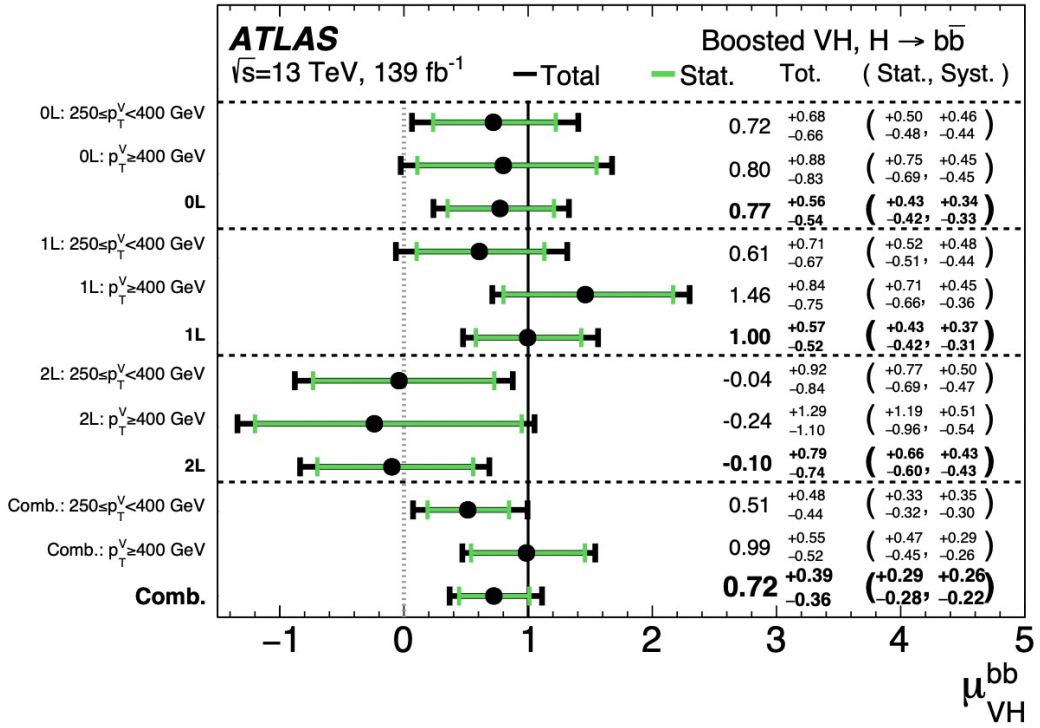
- Background modelling using simulated samples → except for multi-jet in 1-lepton
- Main backgrounds:
  - Top backgrounds → constrained in dedicated control regions
  - W/Z+jets
- Modelling uncertainties assessed though generator comparisons

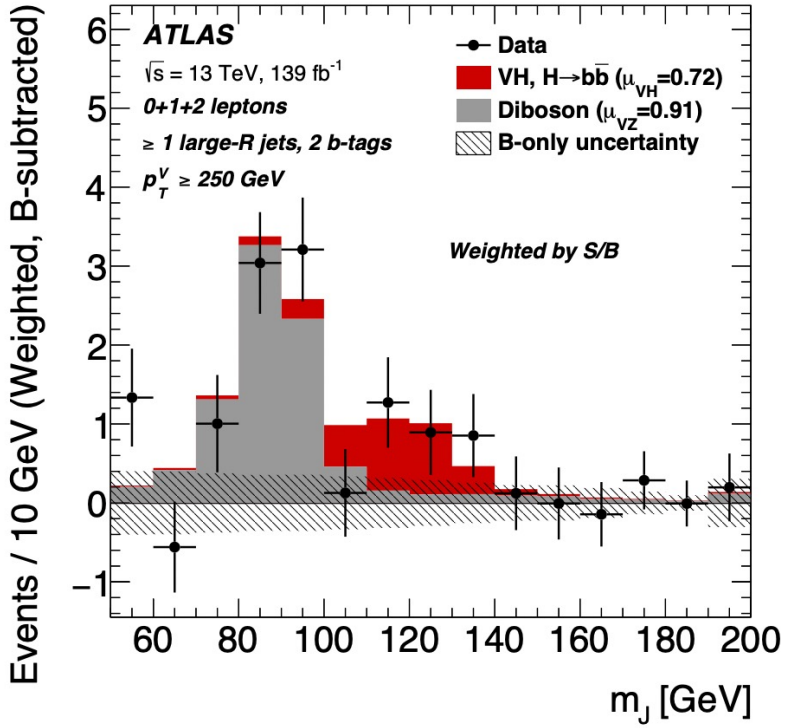
- Signal strength determined using binned likelihood fit to large-R jet mass (m_J) as the discriminant

→ **Simultaneous fit to VH signal and VZ cross-check**



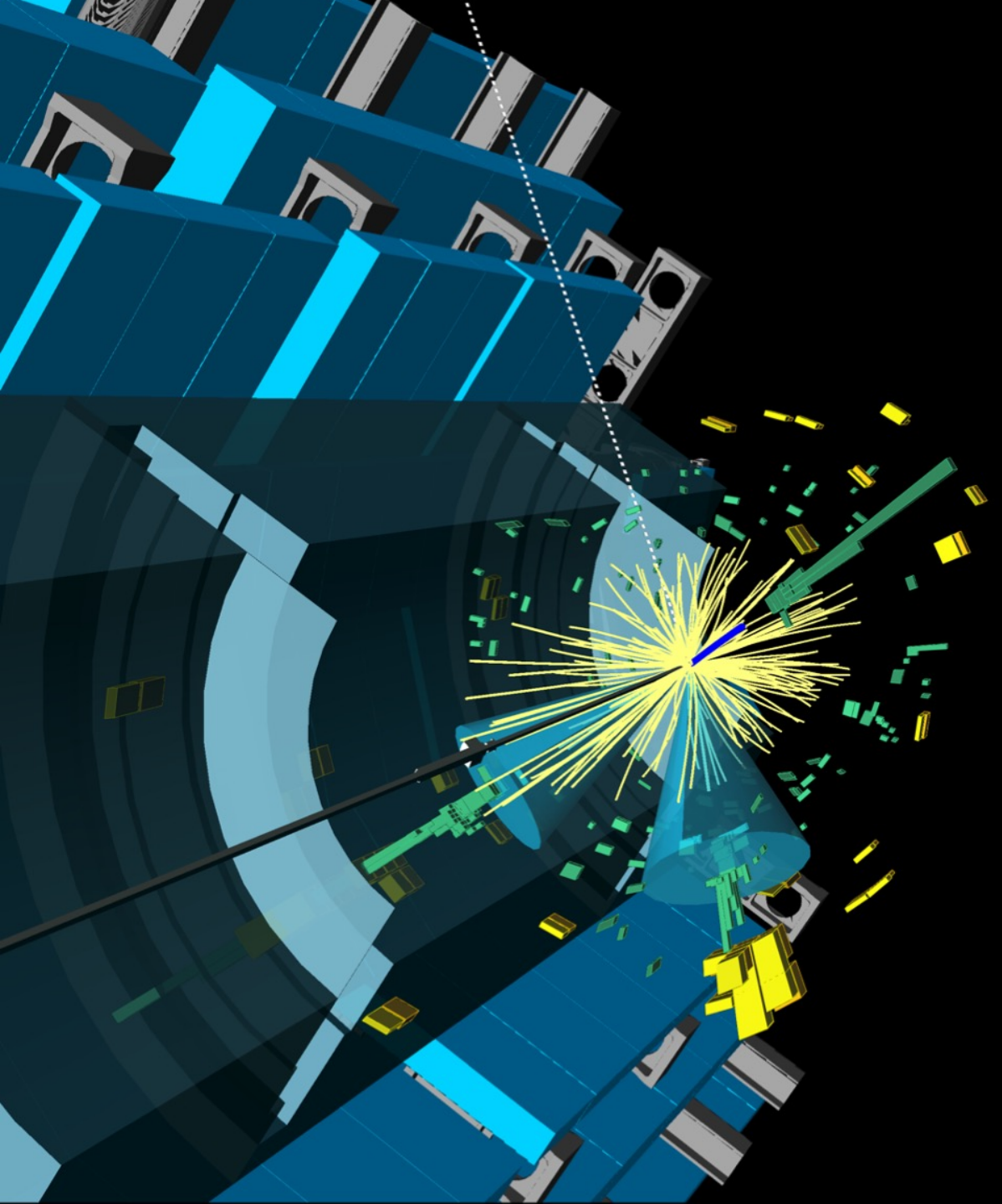
VH(→bb) boosted results





- VZ cross-check measured at 5.4 (5.7) obs. (exp) standard deviations and shows good agreement with SM $\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23}$
- Inclusive VH(bb) measured at 2.1 (2.7) obs. (exp.) standard deviations and $\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.93\ ^{+0.29}_{-0.28}(stat)\ ^{+0.26}_{-0.22}(syst)$

→ Analysis is statistically limited, largest systematics uncertainties from Large R jets and V+jets background modelling



Combination measurements

ATLAS EXPERIMENT

Run: 329964
Event: 500775771
2017-07-18 06:31:13 CEST

Recap of results

- **Resolved VH(bb):**
  - MVA based analysis following H→bb observation strategy
  - Total significance of 6.7σ, WH/ZH measurement, STXS measurement and EFT interpretation
- **Boosted VH(bb):**
  - Cut-based analysis, first iteration of analysis using boosted reconstruction
  - Total observed significance of 2.1σ, STXS measurement and EFT interpretation
- **VH(cc):** (resolved regime)
  - Cut-based analysis, first iteration of this analysis using Full Run 2 dataset and all three lepton channels)
  - Upper Limit of 26 x SM, first direct constraint on $|\kappa_c|<8.5$

VH(→bb) boosted + resolved combination

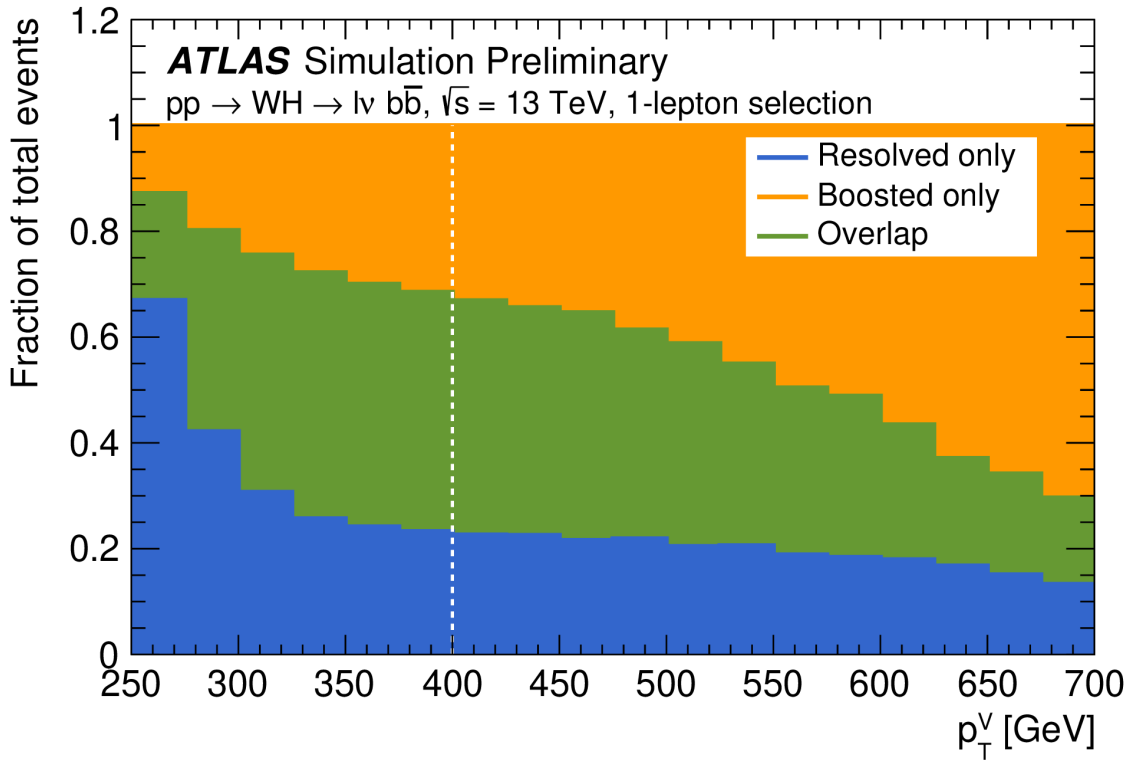
ATLAS-CONF-2021-051

- Combine **resolved and boosted VH(bb) analyses**

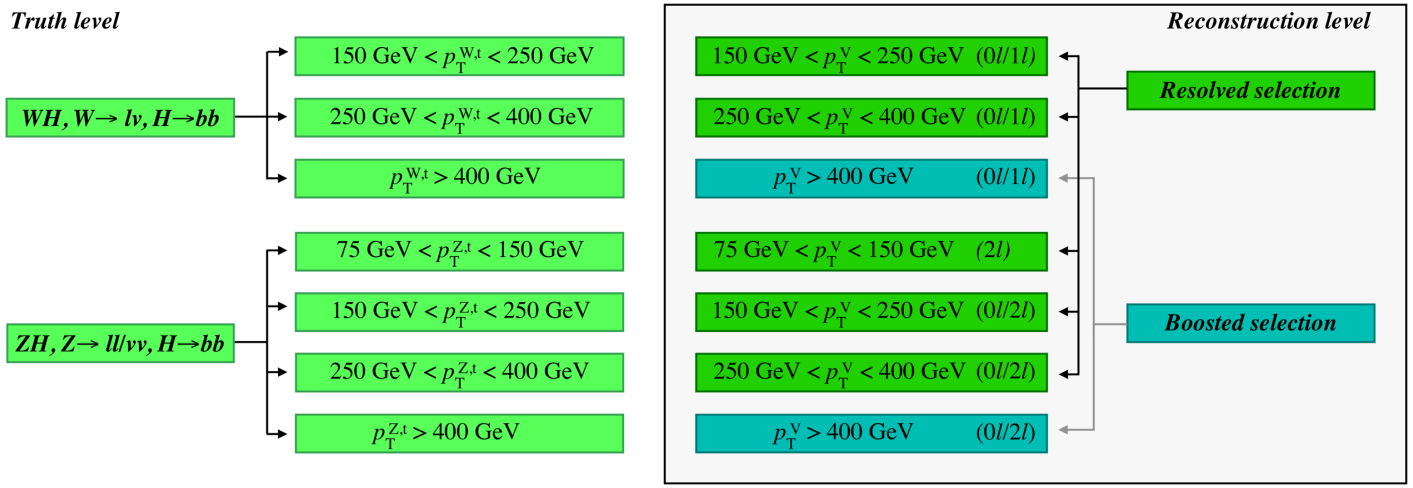
→ Provide a more complete STXS measurement

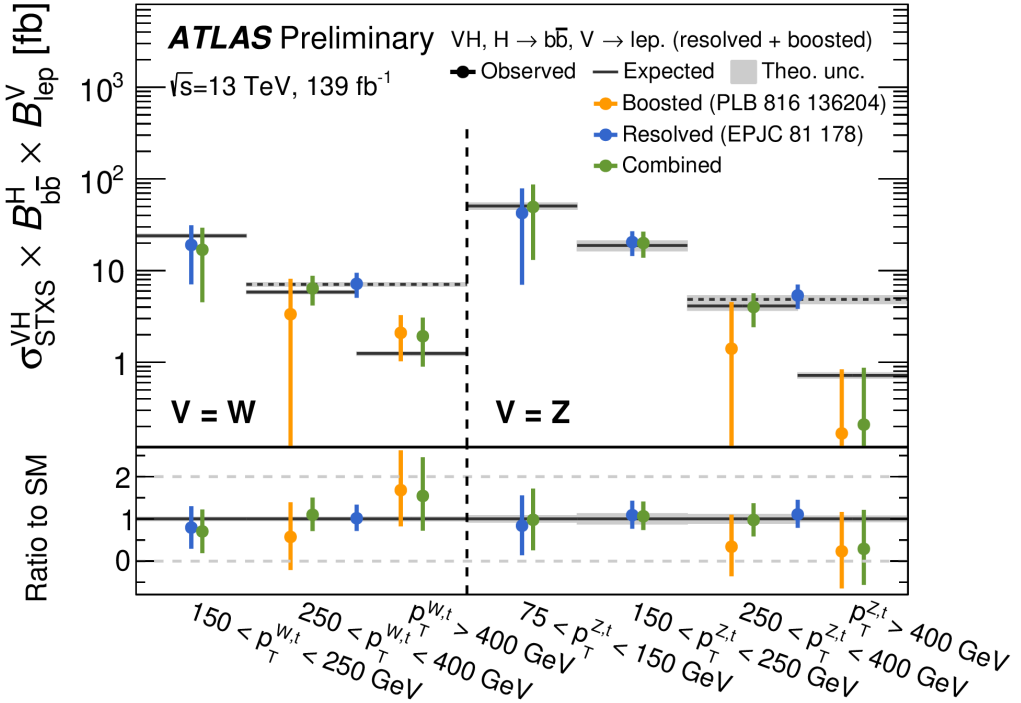
→ Improve sensitivity of EFT interpretation

- **Overlap** between the two analyses resolved by using:
  - Resolved reconstruction for pTV < 400 GeV
  - Boosted reconstruction for pTV > 400 GeV
- Statistical analysis strategy:
  - Floating normalisations reconsidered for a consistent treatment of resolved and boosted regime
  - Experimental uncertainties correlated between the analyses (except b-tagging)
  - Background modelling uncertainties are treated as uncorrelated



VH(→bb) boosted + resolved combination STXS





- STXS measurements in **7 bins of W/Z and $p_T^{W/Z,\,truth}$:**
  - (W,Z) x ([150,250[; [250,400[; [400,inf[) + (Z, [75,150[) GeV
- STXS measurements are compatible with SM expectations, with uncertainties between 30 and 300 %
  - Statistical and systematic uncertainties are similar for pTV < 400 GeV
  - Highest pTV bins are statistically limited
- Additionally: set limits on effective field theory parameters

Resolved VH(→bb) and VH(→cc) combination

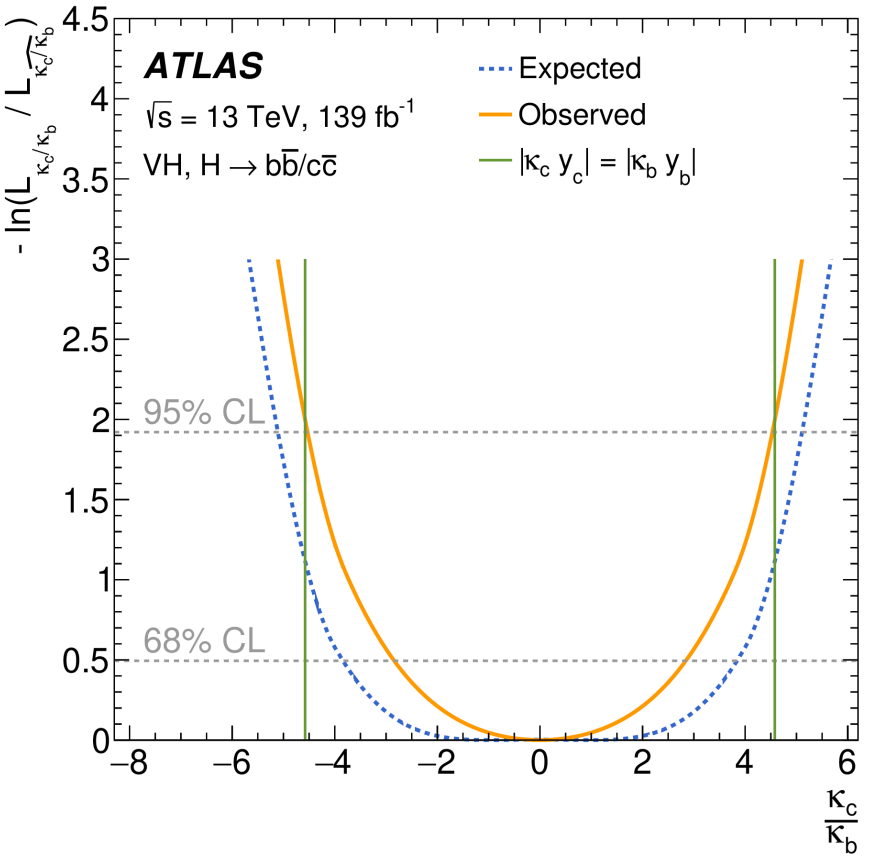
Eur. Phys. J. C 82 (2022) 717

- **Statistical combination of resolved VH(bb) and VH(cc) analyses**
- Allows to simultaneously constrain κ_c and κ_b and utilise the similarity of VH(bb) and VH(cc) decays
- Correlate experimental uncertainties between the two analyses, keep all other uncertainties separate
- Perform fit to κ_c/κ_b
- Test of b/c universality

→ if the Higgs boson couples equally to b- and c-quarks κ_c/κ_b must be 4.5

→ **Higgs boson coupling to c-quarks smaller than to b-quarks at 95% CL**

Likelihood scan of κ_c/κ_b



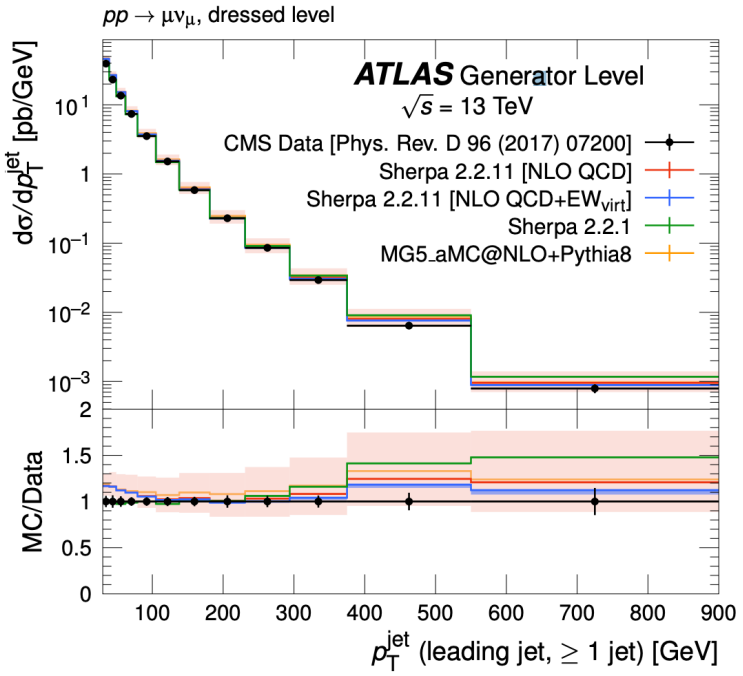
Sneak peak: V+jets

V+jets background modelling is critical for both the VH(bb) and VH(cc) analyses

Several recent developments in V+jets event generation in ATLAS (details here)

- **Sherpa 2.2.11 setup** with several improvements:
  - Corrected heavy flavour hadron production fractions
  - Inclusion of higher-order QCD and EW corrections, updated EW input scheme, and additional specialised treatments
  - Additional computational improvements reduce CPU resources needed per event
- **MadGraph5_aMC@NLO+Pythia8** w/ up to 3 additional partons at NLO, using FxFx ME and PS merging prescription, is also available as an alternative generator

Comparison of different Sherpa and MadGraph setups in comparisons to W+jets data



Mean CPU time per event for Sherpa 2.2.1 and 2.2.11

Phase-space strategy	Mean [s/event]	Mean [HS06 s/event]	Fraction of events [%]
SHERPA 2.2.11 configuration			
$\left(\frac{\max(H_T, p_T^V)}{20}\right)^2$ analytic enhancement	17.9 ± 0.2	375 ± 4	100
SHERPA 2.2.1 configuration			
$0 < \max(H_T, p_T^V) < 70$ GeV	4.7 ± 0.5	99 ± 11	31
$70 < \max(H_T, p_T^V) < 140$ GeV	34.6 ± 2.3	725 ± 48	27
$140 < \max(H_T, p_T^V) < 280$ GeV	36.8 ± 1.2	772 ± 25	19
$280 < \max(H_T, p_T^V) < 500$ GeV	53.7 ± 2.2	1126 ± 46	11
$500 < \max(H_T, p_T^V) < 1000$ GeV	67.6 ± 3.0	1418 ± 63	9
$\max(H_T, p_T^V) > 1000$ GeV	108.4 ± 5.7	2273 ± 120	3

Summary

- Discussed the current results of VH(bb) and VH(cc) measurements in ATLAS
- **Resolved VH(bb):**
  - MVA based analysis following H→bb observation strategy
  - Total significance of 6.7σ, WH/ZH measurement, STXS measurement and EFT interpretation
- **Boosted VH(bb):**
  - Cut-based analysis, first iteration of analysis using boosted reconstruction
  - Total observed significance of 2.1σ, STXS measurement and EFT interpretation
- **VH(cc):** (resolved regime)
  - Cut-based analysis, first iteration of this analysis using Full Run 2 dataset and all three lepton channels)
  - Upper Limit of 26 x SM, first direct constraint on $|\kappa_c|<8.5$
- V+jets modelling plays a critical role in all of these analyses → discussed modelling uncertainties and future improvements
- Performed first statistical combinations of resolved + boosted VH(bb), resolved VH(bb) + VH(cc)

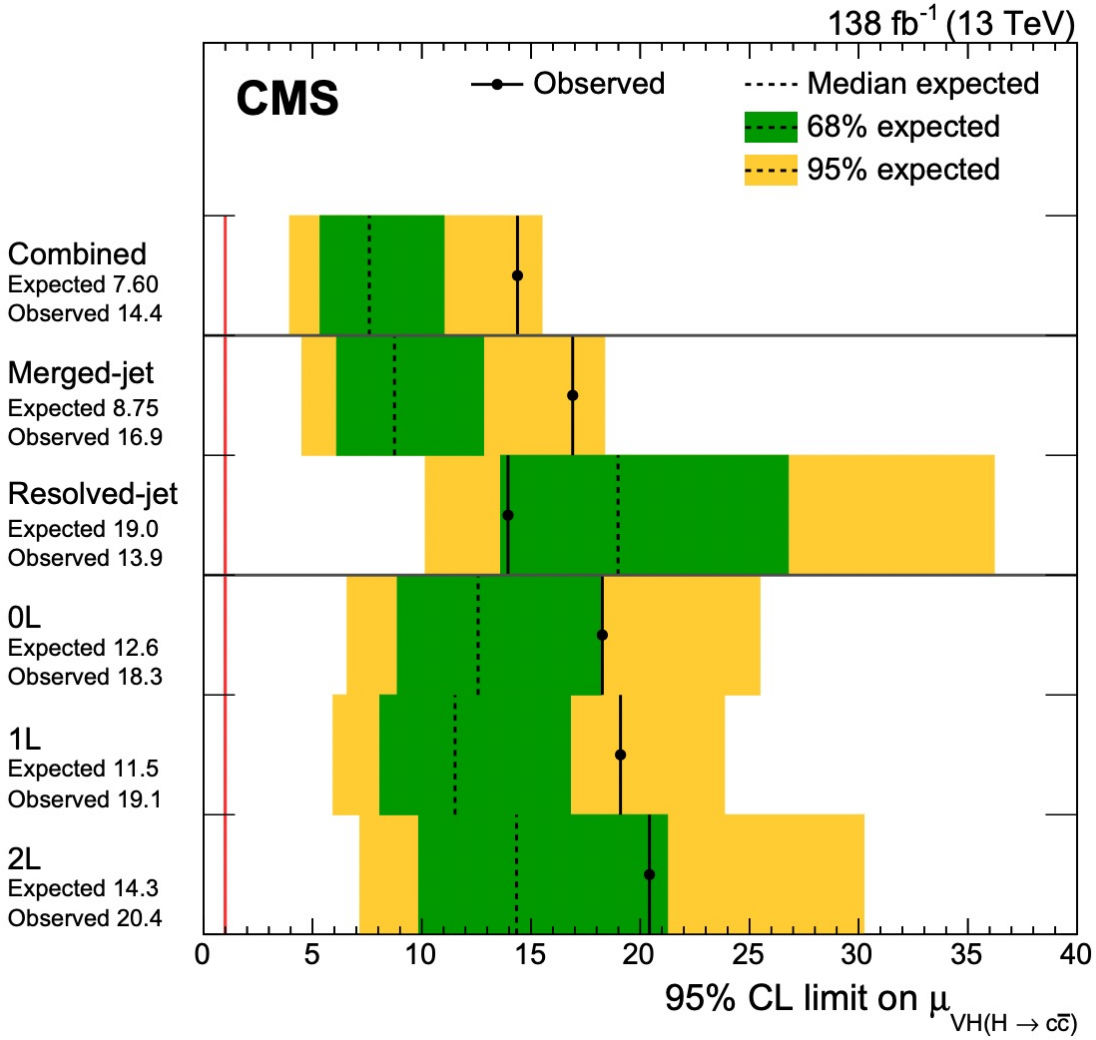
Stay tuned!

Thank you!

Any questions?

VH(cc) backup

CMS VH(cc)



Uncertainty source	$\Delta\mu / (\Delta\mu)_{tot}$
Statistical	85%
Background normalizations	37%
Experimental	48%
Sizes of the simulated samples	37%
c jet identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Integrated luminosity	6%
Lepton identification efficiencies	4%
Theory	22%
Backgrounds	17%
Signal	15%

CMS breakdown

Compare breakdown of uncertainties to understand key difference in sensitivity

Comparison – CMS total

	Total impact		Fractional impact	
	ATLAS 139 /fb Total ± 15.3	CMS 138 /fb Total ± 3.6	ATLAS 139 /fb	CMS 138 /fb
Data stat	± 10.0	± 3.3	± 0.43	± 0.85
Data stat only	± 7.9	± 3.2	± 0.26	± 0.77
Floating norms	± 5.1	± 2.1	± 0.11	± 0.37
Modelling	± 9.05	± 1.8	± 0.350	± 0.25
Signal	± 2.10	± 1.4	± 0.019	± 0.15
Background	± 8.80	± 1.5	± 0.330	± 0.17
Simulation modelling	-	± 1.2	-	± 0.11
MC stat	± 4.23	± 2.1	± 0.076	± 0.37
Experimental systs	± 5.18	± 2.5	± 0.115	± 0.48
Lepton	± 0.49	± 0.7	± 0.001	± 0.04
MET	± 0.18	- *	± 0.0001	-
JET	± 2.84	± 1.4	± 0.034	± 0.15
Pile-up/Lumi	± 0.29	± 0.7	± 0.0003	± 0.04
FTAG (+TT)	± 4.29	± 1.7	± 0.079	± 0.23
FTAG	± 2.06	± 1.7	± 0.018	± 0.23
TT dR / DT	± 3.76	-	± 0.060	-

CMS breakdown

Comparison – CMS resolved

	Total impact		Fractional impact	
	ATLAS 139 /fb Total ± 15.3	CMS 138 /fb Total ± 9.6	ATLAS 139 /fb	CMS 138 /fb
Data stat	± 10.0	± 7.7	± 0.43	± 0.66
Data stat only	± 7.9	± 7.4	± 0.26	± 0.60
Floating norms	± 5.1	± 5.1	± 0.11	± 0.28
Modelling	± 9.05	± 5.2	± 0.350	± 0.29
Signal	± 2.10	± 2.5	± 0.019	± 0.07
Background	± 8.80	± 4.4	± 0.330	± 0.21
Simulation modelling	-	± 4.3	-	± 0.20
MC stat	± 4.23	± 7.4	± 0.076	± 0.59
Experimental systs	± 5.18	± 8.1	± 0.115	± 0.72
Lepton	± 0.49	± 3.0	± 0.001	± 0.10
MET	± 0.18	- *	± 0.0001	-
JET	± 2.84	± 3.9	± 0.034	± 0.17
Pile-up/Lumi	± 0.29	± 3.5	± 0.0003	± 0.13
FTAG (+TT)	± 4.29	± 4.9	± 0.079	± 0.27
FTAG	± 2.06	± 4.9	± 0.018	± 0.27
TT dR / DT	± 3.76	-	± 0.060	-

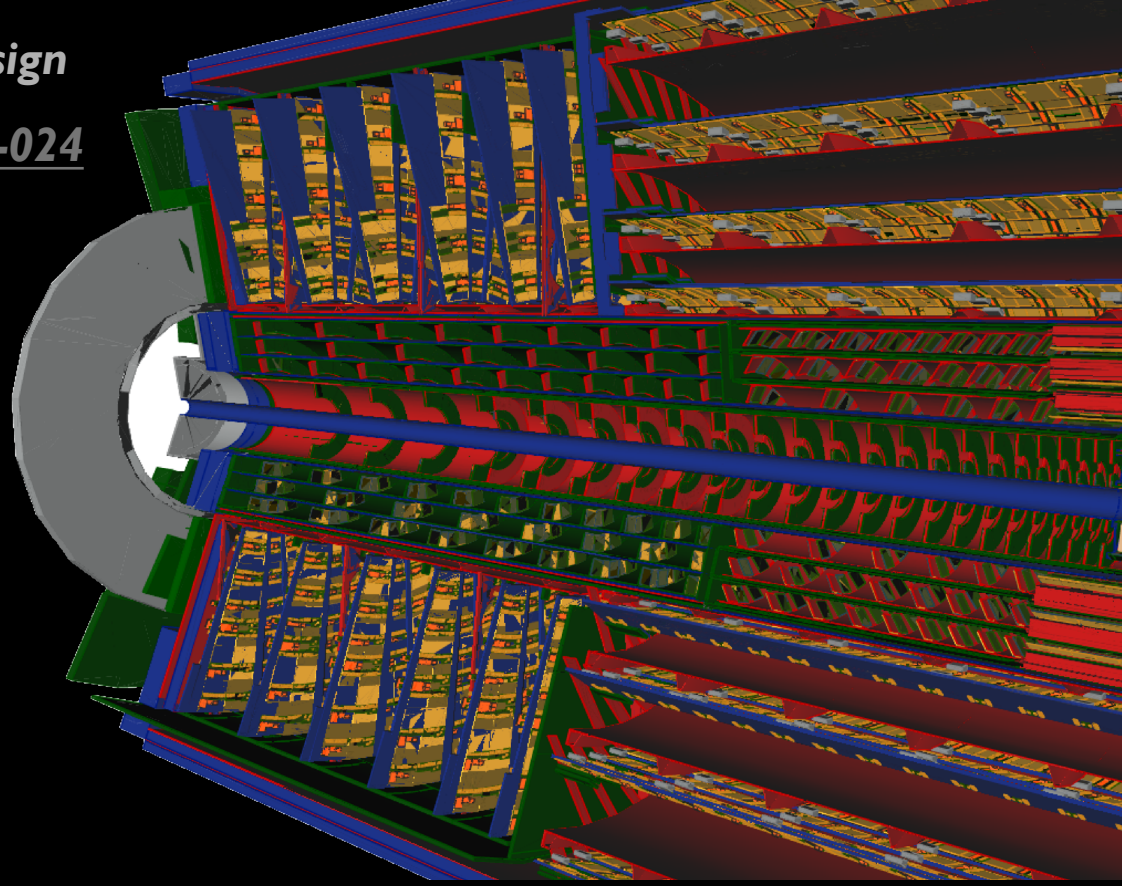
CMS breakdown

Comparison – CMS boosted

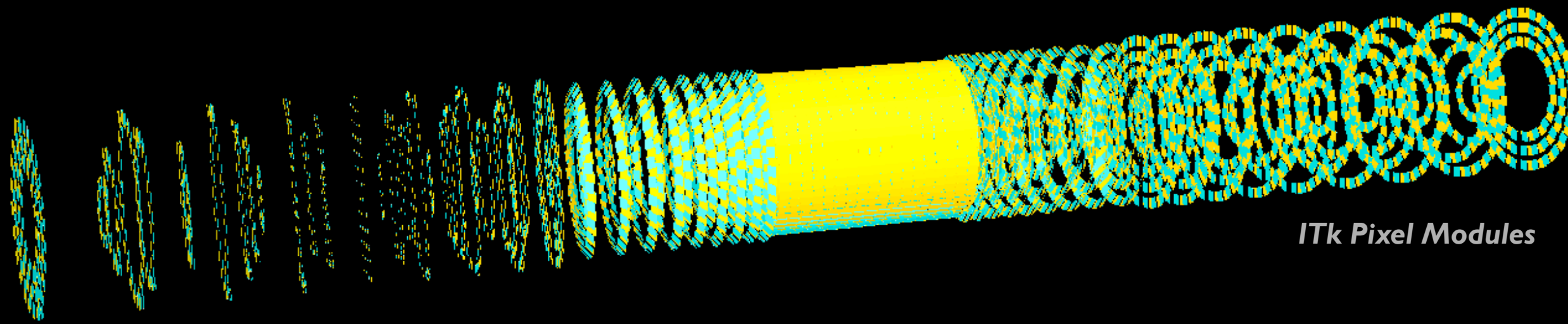
	Total impact		Fractional impact	
	ATLAS 139 /fb Total ± 15.3	CMS 138 /fb Total ± 4.3	ATLAS 139 /fb	CMS 138 /fb
Data stat	± 10.0	± 4.0	± 0.43	± 0.88
Data stat only	± 7.9	± 3.8	± 0.26	± 0.78
Floating norms	± 5.1	± 2.7	± 0.11	± 0.39
Modelling	± 9.05	± 2.2	± 0.350	± 0.25
Signal	± 2.10	± 1.6	± 0.019	± 0.14
Background	± 8.80	± 2.0	± 0.330	± 0.21
Simulation modelling	-	± 0.4	-	± 0.01
MC stat	± 4.23	± 2.1	± 0.076	± 0.24
Experimental systs	± 5.18	± 2.7	± 0.115	± 0.40
Lepton	± 0.49	± 0.6	± 0.001	± 0.02
MET	± 0.18	- *	± 0.0001	-
JET	± 2.84	± 1.7	± 0.034	± 0.15
Pile-up/Lumi	± 0.29	± 1.0	± 0.0003	± 0.05
FTAG (+TT)	± 4.29	± 2.2	± 0.079	± 0.26
FTAG	± 2.06	± 2.2	± 0.018	± 0.23
TT dR / DT	± 3.76	-	± 0.060	-

Latest current ITk design

ATL-PHYS-PUB-2021-024



Prospects for HL-LHC



ITk Pixel Modules

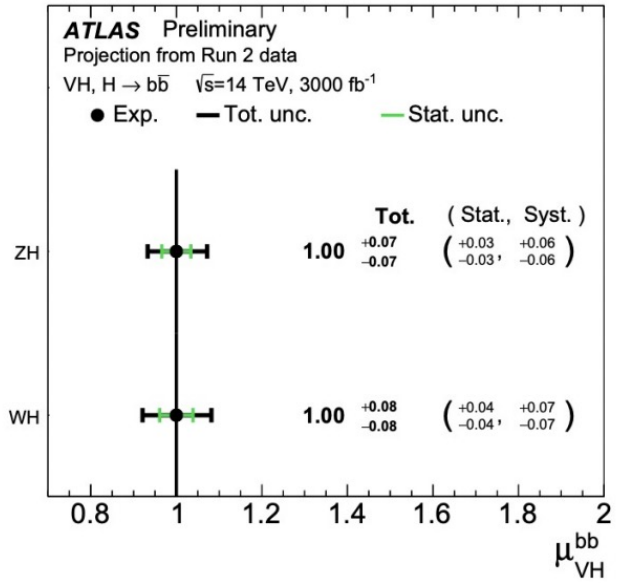
VH(bb) extrapolation

- Extrapolation based on published Run 2 VH(bb) analysis

Fit to WH(bb) and ZH(bb) signal strengths:

- **Uncertainties of 7% for ZH and 8% for WH**
- *Full Run 2 result: uncertainties of 25% for ZH and 26% for WH*
- Leading uncertainties: Signal modelling, followed by flavour tagging

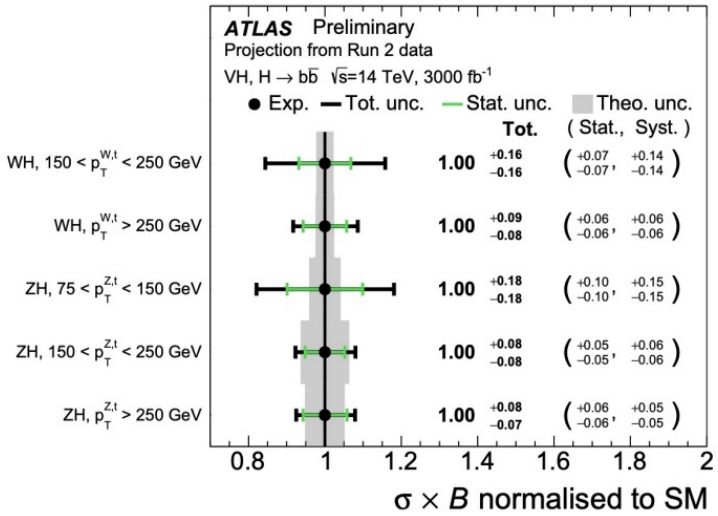
WH/ZH extrapolation

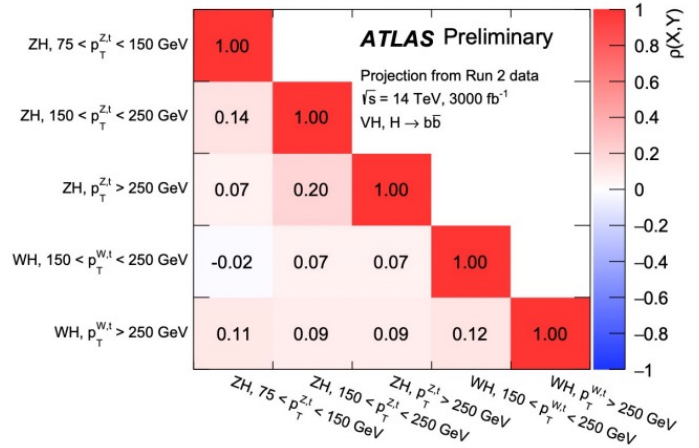


Fit to signal strengths in 5 STXS bins:

- **Uncertainties vary between 18% in the low p_T bins and 7% in the high p_T bins**
- *Full Run 2 result: uncertainties between 30-60%*

VH(bb) STXS extrapolation

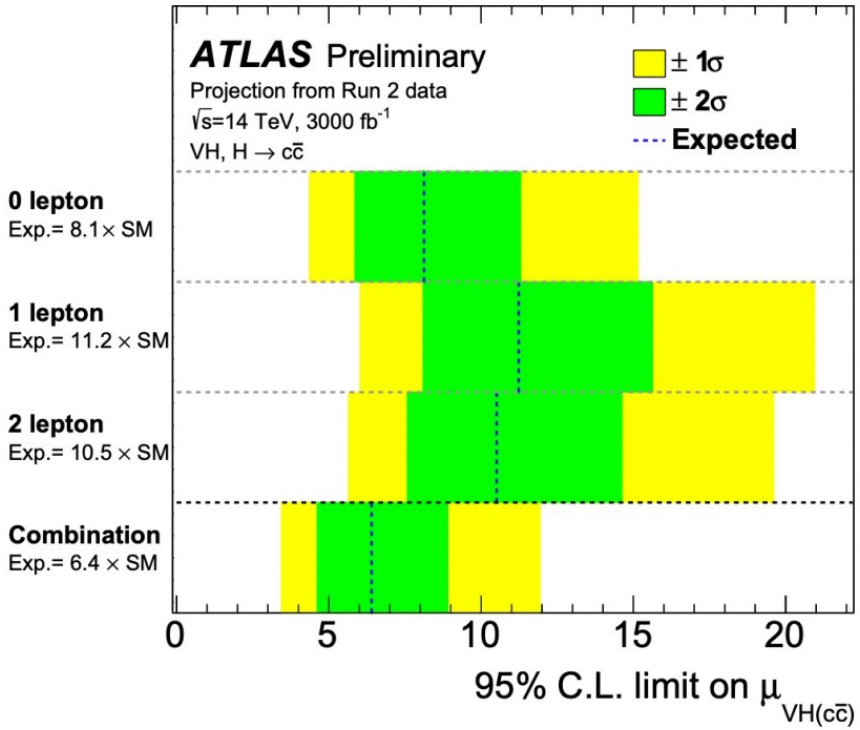




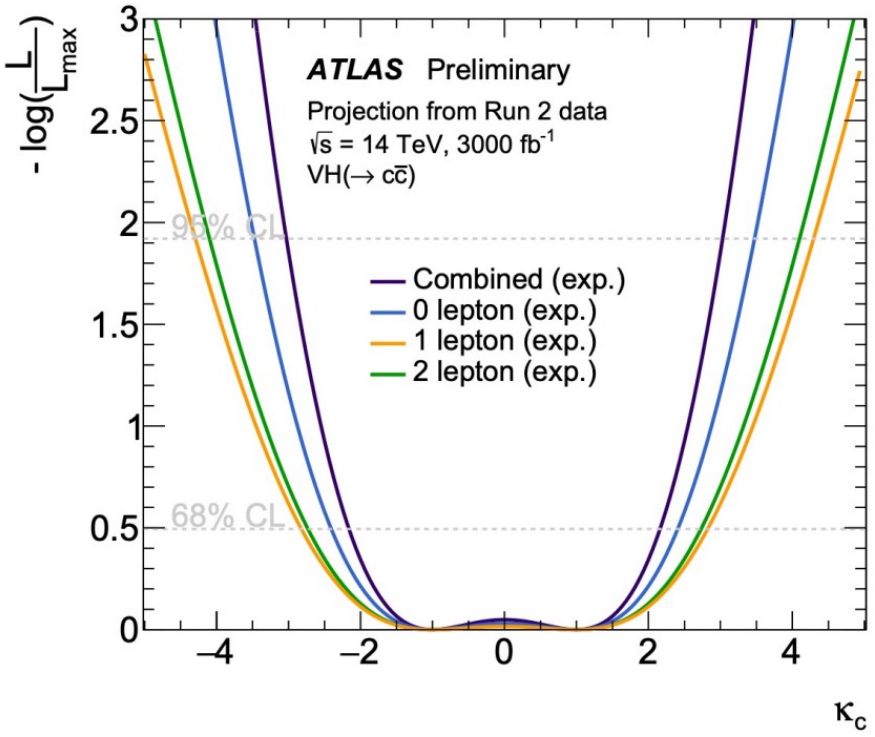
VH(cc) extrapolation

- Extrapolation based on public Run 2 VH(cc) analysis
- Expected upper limit on VH(cc) signal strength of 6.4 x SM and $|\kappa_c| < 3.0$
- Leading uncertainties from Z+jets modelling and flavour tagging

Limits on $\mu_{VH(cc)}$



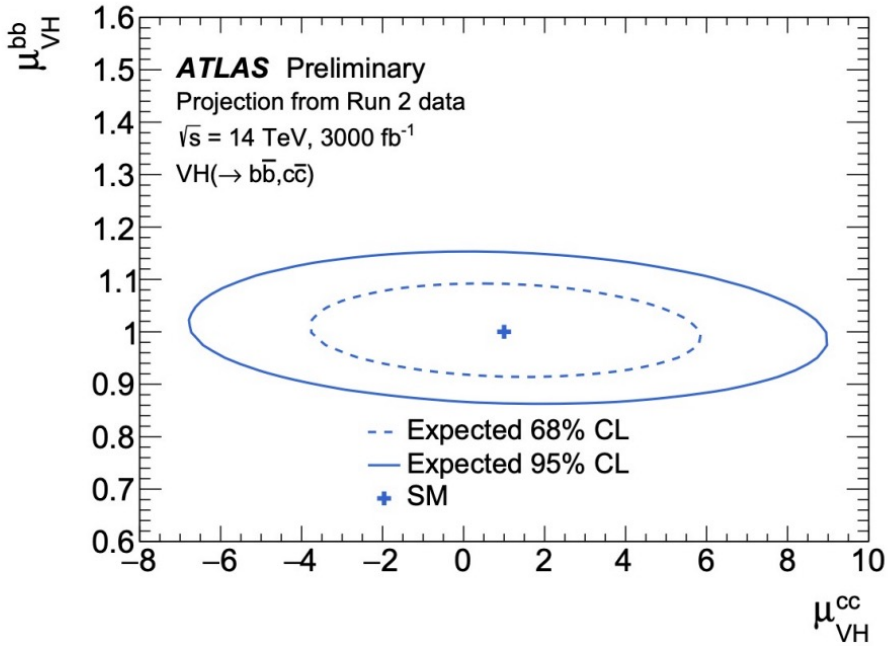
Likelihood scan of κ_c



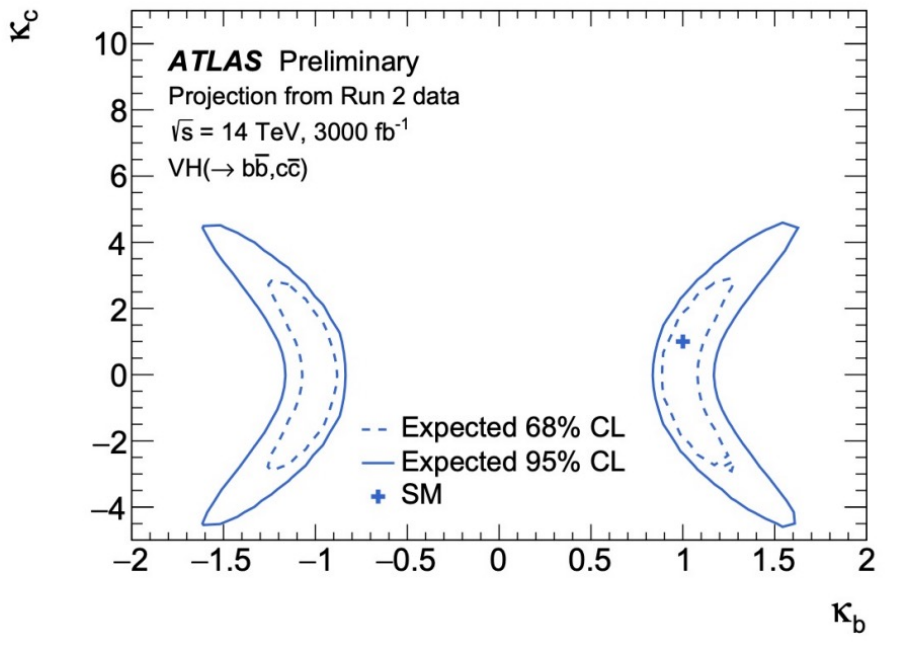
VH(bb/cc) combination

- Given the similarity of the VH(bb) and VH(cc) analyses it is straightforward to perform a simple statistical combination
- At HL-LHC expect $\mu_{VH(bb)} = 1.00 \pm 0.06$ and $\mu_{VH(cc)} = 1.00 \pm 3.20$
- Expected constraint of $|\kappa_c/\kappa_b| < 2.74$ at 95% CL

Likelihood scan of $\mu_{VH(cc)}$ and $\mu_{VH(bb)}$



Likelihood scan of κ_c and κ_b



MC samples

- **V+jets:** (Details)
  - Nominally simulated with Sherpa 2.2.1
    - NLO-accurate matrix elements for up to 2 jets, LO-accurate ME for up to four jets in five-flavour scheme are calculated with Comix
    - b- and c-quarks are treated as massless
    - QCD corrections for ME @ NLO by OpenLoops
    - NNPDF3.0NNLO PDF
    - Max(H_T, p_T^V) slides with boundaries [0, 70, 140, 280, 500, 1000, 6500] GeV
  - Alternative samples simulated with MadGraph5_aMC@NLO 2.6.5
    - Showering and hadronisation with Pythia 8.240 with A14 tune and NNPDF2.3LO PDF set
    - Full 5-flavour scheme with massless quarks in ME calculation

Summary of Sherpa configurations

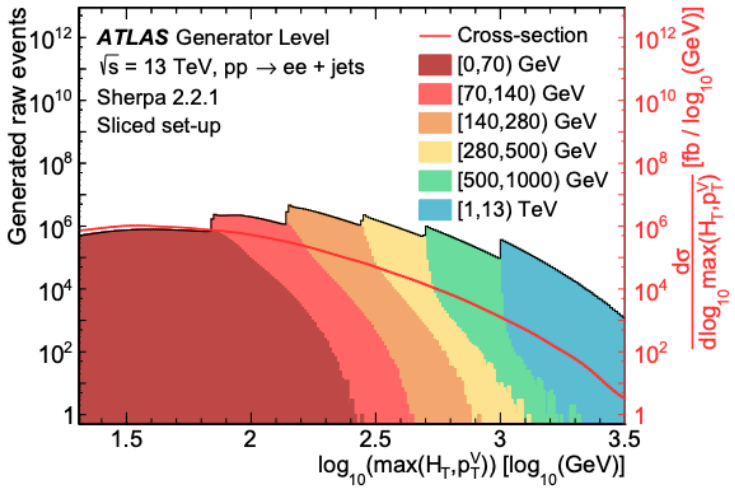
https://arxiv.org/pdf/2112.09588.pdf

Table 1: Summary of the SHERPA 2.2.1 and 2.2.11 configurations.

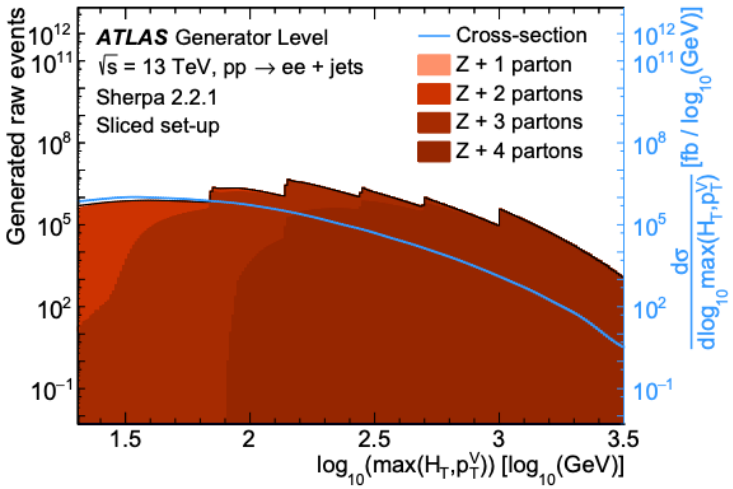
Configuration	SHERPA 2.2.1	SHERPA 2.2.11
Generator version	SHERPA 2.2.1	SHERPA 2.2.11
PDF set	NNPDF3.0NNLO	NNPDF3.0NNLO
EW input scheme	Effective	$\sin^2\theta_{\text{eff}}$
QCD accuracy	0–2j@NLO+3,4j@LO	0–2j@NLO+3,4,5j@LO
NLO EW_{virt} corrections	No	Yes
Subtraction scheme	Default	Modified Catani–Seymour
Special treatment for unordered histories	No	Yes
Scale for $\mathbb{H}$-events	STRICT_METS	H'_{T}
Gluon colour/spin exact matching	Yes	No
Core process for K-factor	$2 \to 4$	$2 \to 2$
Phase-space strategy	Sliced in $\max(H_{\text{T}}, p_{\text{T}}^{V})$	Analytic enhancement

Phase space sampling

https://arxiv.org/pdf/2112.09588.pdf



(a) Boundary Breakdown



(b) Jet Multiplicity Breakdown

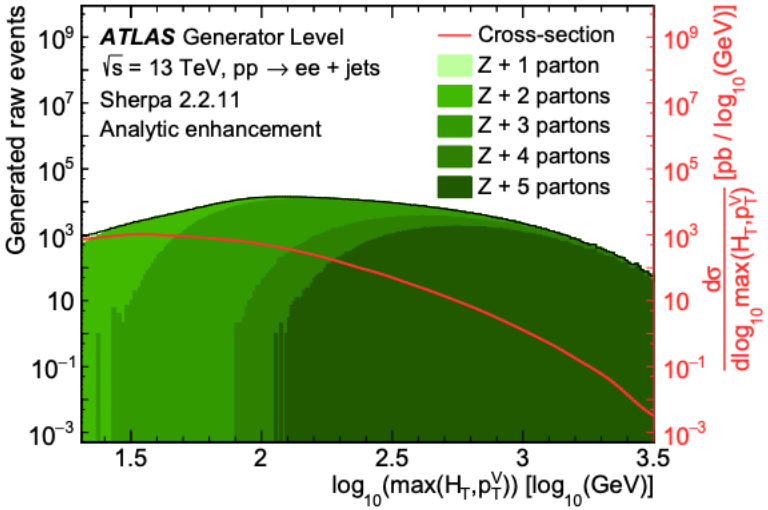


Figure 10: Distribution of unweighted $pp \to e^+e^-$ + jets MC sampled events and differential cross-section for the sliced enhancement as a function of the slicing observable, $\log_{10}(\max(H_T, p_T^V))$. Events are sliced according to the $\max(H_T, p_T^V)$ variable. The unweighted distribution is split either (a) according to the phase-space sampling slices, or (b) according to the final-state jet multiplicity. In (b) the Z+1 parton contribution is small and only visible in the top left of the distribution.

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

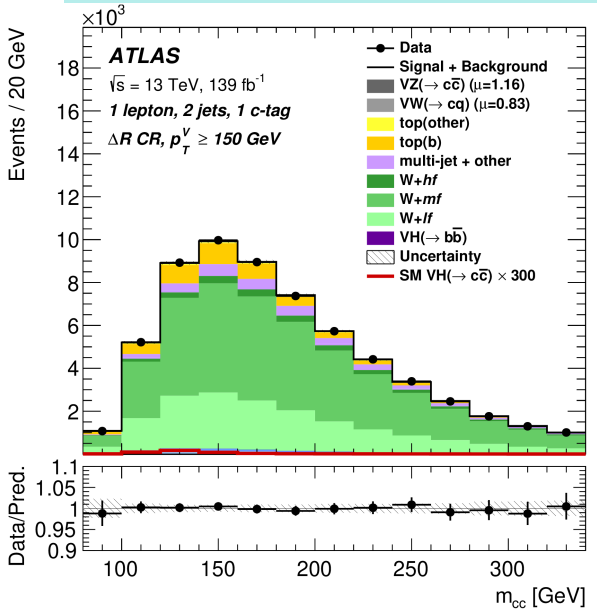
Common Selections	
Central jets	≥ 2
Signal jet p_{T}	≥ 1 signal jet with $p_{\mathrm{T}} > 45$ GeV
c-jets	1 or 2 c-tagged signal jets
b-jets	No b-tagged non-signal jets
Jets	2, 3 (0- and 1-lepton), 2, ≥ 3 (2-lepton)
p_{T}^{V} regions	75–150 GeV (2-lepton) > 150 GeV
ΔR(jet 1, jet 2)	$75 < p_{\mathrm{T}}^{V} < 150$ GeV: $\Delta R \leq 2.3$ $150 < p_{\mathrm{T}}^{V} < 250$ GeV: $\Delta R \leq 1.6$ $p_{\mathrm{T}}^{V} > 250$ GeV: $\Delta R \leq 1.2$
0 Lepton	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	0 *loose* leptons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV
$p_{\mathrm{T}}^{\mathrm{miss}}$	> 30 GeV
H_{T}	> 120 GeV (2 jets), > 150 GeV (3 jets)
$\min \lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})\rvert$	$> 20°$ (2 jets) , $> 30°$ (3 jets)
$\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, H)\rvert$	$> 120°$
$\lvert\Delta\phi(\mathrm{jet1}, \mathrm{jet2})\rvert$	$< 140°$
$\lvert\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}})\rvert$	$< 90°$
1 Lepton	
Trigger	e sub-channel: single electron μ sub-channel: $E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	1 *tight* lepton and no additional *loose* leptons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 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

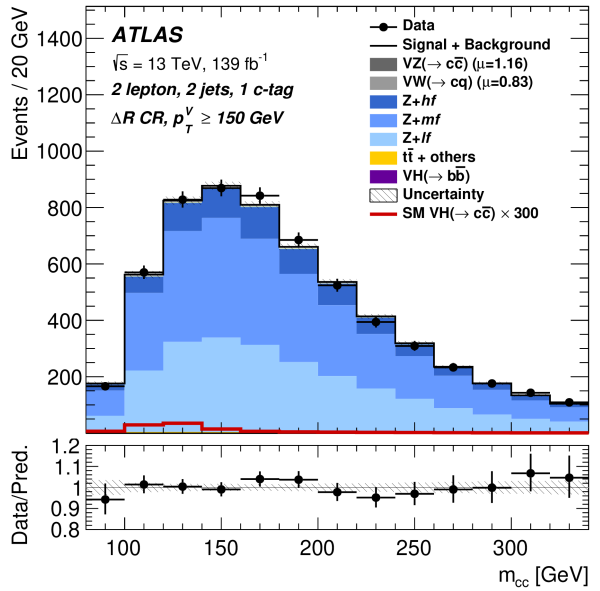
$VH(\rightarrow b\bar{b})$	
$WH(\rightarrow b\bar{b})$ normalisation	27%
$ZH(\rightarrow b\bar{b})$ normalisation	25%
Diboson	
$WW/ZZ/WZ$ acceptance	10/5/12%
p_{T}^{V} acceptance	4%
N_{jet} acceptance	7 – 11%
Z+jets	
Z+hf normalisation	Floating
Z+mf normalisation	Floating
Z+lf normalisation	Floating
$Z + bb$ 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%

V+jets background

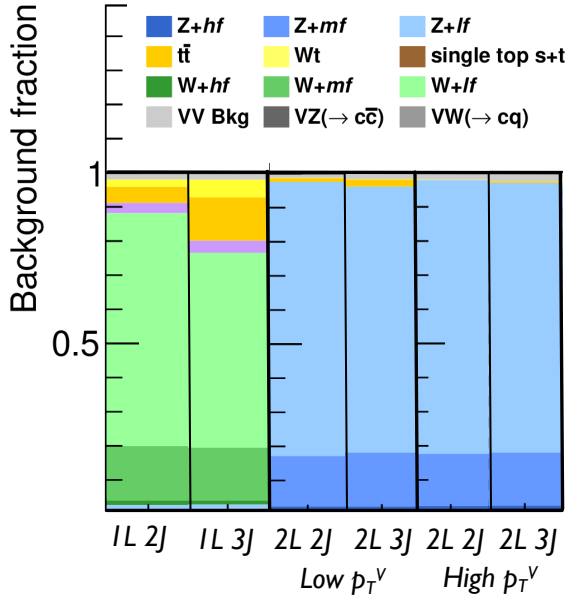
- V+jets (split as W and Z+jets) split into flavours:
  - **V+hf:V+cc,** V+bb
  - **V+mf:V+cl,** V+bc,V+bl [1]
  - **V+lf** [2]
- All V+jets normalisations floating in fit, separated as V+hf,V+mf and V+lf
- V+hf and V+mf floating normalisations determined with the help of a **high ΔR_{cc} control region**
- 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: $1.2 < \Delta R_{cc} < 2.5$
- Upper cut added to stay close to SR phase space
- V+lf floating normalisations determined **in 0 c-tag CR** and 1 and 2 lepton → same kinematic selection as SR

High ΔR_{cc} control region (postfit)





0 c-tag CR



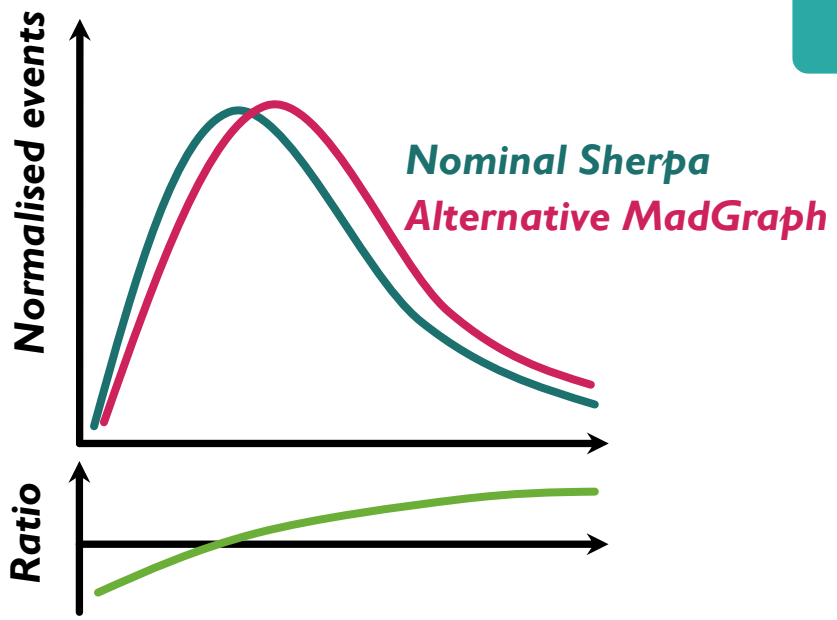
[1] *including W(τν)+b,W(τν)+c in 0 lepton*

[2] *including W(τν)+l in 0 lepton*

V+jets m_{cc} shape uncertainties

- Extrapolation from ΔR CR to SR is more complicated, as m_{cc} and ΔR_{cc} are correlated
- Two sets of shape uncertainties defined, from comparisons of Sherpa2.2.1 and MadGraph5

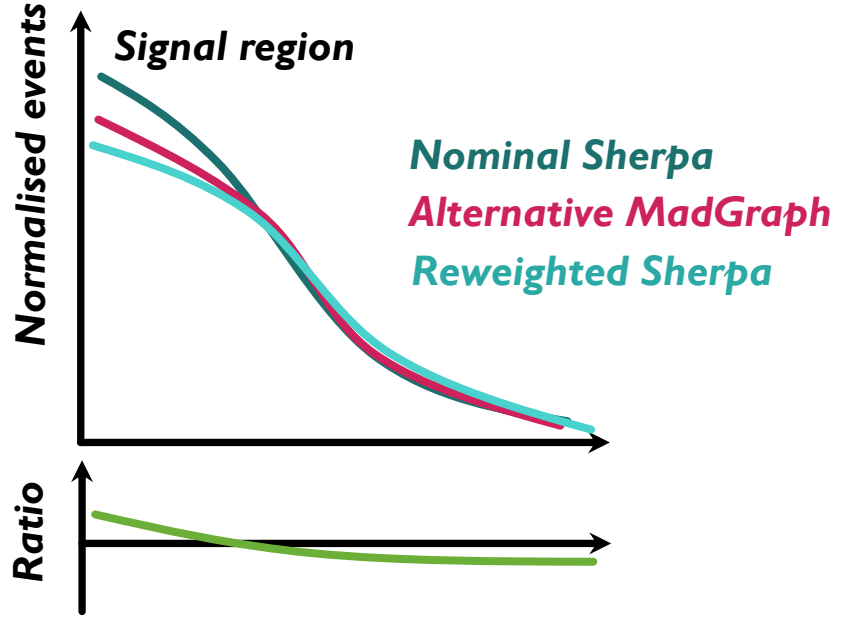
Systematic 1



- Derived in the ΔR CR, applied to SR and ΔR CR, correlated shape+normalisation effect

→ Provides constraints on m_{cc} shape in SR from ΔR CR, and takes care of acceptance effect

Systematic 2



- Reweight Sherpa MC in the SR by Syst I and calculate residual difference to MG
- Applied to SR only as shape-only

→ Provides additional freedom on m_{cc} shape in SR

V+jets normalisations

- All V+jets normalisations floating in fit and constrained from signal and control regions
- Common normalisations for all data-taking periods, as SRs are not split by years
- Decorrelations between n_{jet} and p_T^V regions as much as possible within the stat uncertainties
- Nominal MC generator is **Sherpa 2.2.1**
- **0- and 1-lepton:**
  - Common normalisations for all categories for W+hf and W+mf
  - Separate floating normalisations for W+lf in n_{Jet} due to 0 c-tag CR with high statistics
- **0- and 2-lepton:**
  - Floating normalisations split by p_T^V categories (low p_T^V only in 2-lepton)
  - Split normalisations in n_{Jet} for Z+lf

W+jets floating normalisations

Background	p_T^V	Jets	Value
W+hf			1.16 ± 0.35
W+mf			1.28 ± 0.35
W+lf		2	1.02 ± 0.04
		3	0.97 ± 0.05

Z+jets floating normalisations

Background	p_T^V	Jets	Value
Z+hf	>150 GeV		1.19 ± 0.22
	75-150 GeV		1.25 ± 0.25
Z+mf	>150 GeV		1.10 ± 0.15
	75-150 GeV		1.11 ± 0.15
Z+lf	>150 GeV	2	**1.07 ± 0.03**
		3	**1.08 ± 0.05**
	75-150 GeV	2	**1.12 ± 0.04**
		3	**1.07 ± 0.06**

*Most normalisations in agreement with 1 (**highlighted** otherwise)*
Similar normalisations also seen in VH(bb) with smaller uncertainties

V+jets uncertainties

- **Acceptance ratios** between channels, flavour components and jet multiplicity categories
- Comparison of Sherpa 2.2.1 and MadGraph5 and μ_R, μ_F scale variations
- **m_{cc} shape uncertainties** derived from the same sources
- Largest uncertainties from Sherpa/MadGraph comparisons, followed by μ_R scale variation

	Uncertainty	Prior
Z+jets	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 %
	0-lepton/2-lepton ratio	4-5 %
W+jets	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(τν)+c to W+cl ratio	11 %
	W(τν)+b to W+cl ratio	27 %
	W(τν)+l to W+l ratio	8 %
	n_{Jet} acceptance	8-14 %
	W(τν) SR/ΔR CR ratio	5-18 %
	0-lepton/1-lepton ratio	1-6 %

Truth-tagging

- Due to moderate c-tagging efficiency (27%), the available MC statistics are significantly reduced in the VH(cc) analysis

→ Additional MC statistics, especially for V+jets, would mean a significant improvement

- Mitigation possible through the use of **truth-tagging**

→ Instead of using direct cut on flavour tagging requirements (direct tagging), weigh event based on probability of passing c-tagging

- Weights calculated from flavour tagging efficiency stored in 2D map as function of p_T and η
- Used in VH(cc) analysis to improve statistical uncertainty on simulated background events for V+jets and other backgrounds by ~ factor 3
- Also used in VH(bb) on non-b jets ("hybrid tagging")
- Closure with direct tagging not perfect → requires additional uncertainties
- Recent promising developments in truth-tagging using GNN

c-tagging efficiency as a function of jet p_T

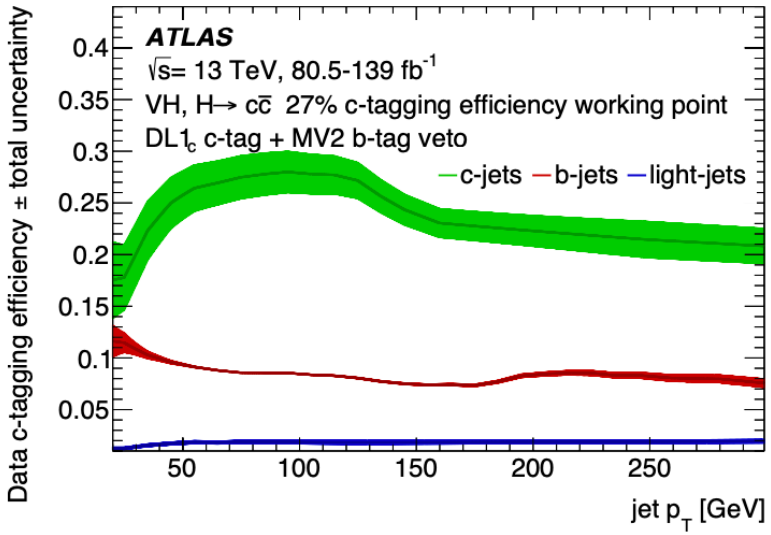
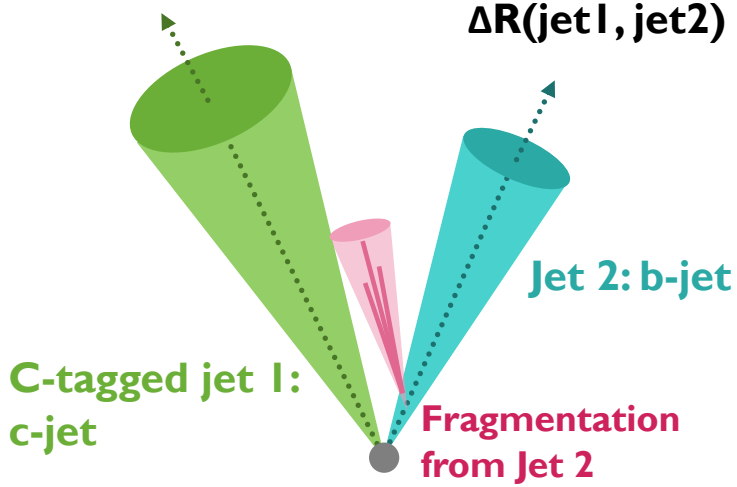


Illustration of close-by jets which can cause disagreement with direct and truth tagging



BDTr approach

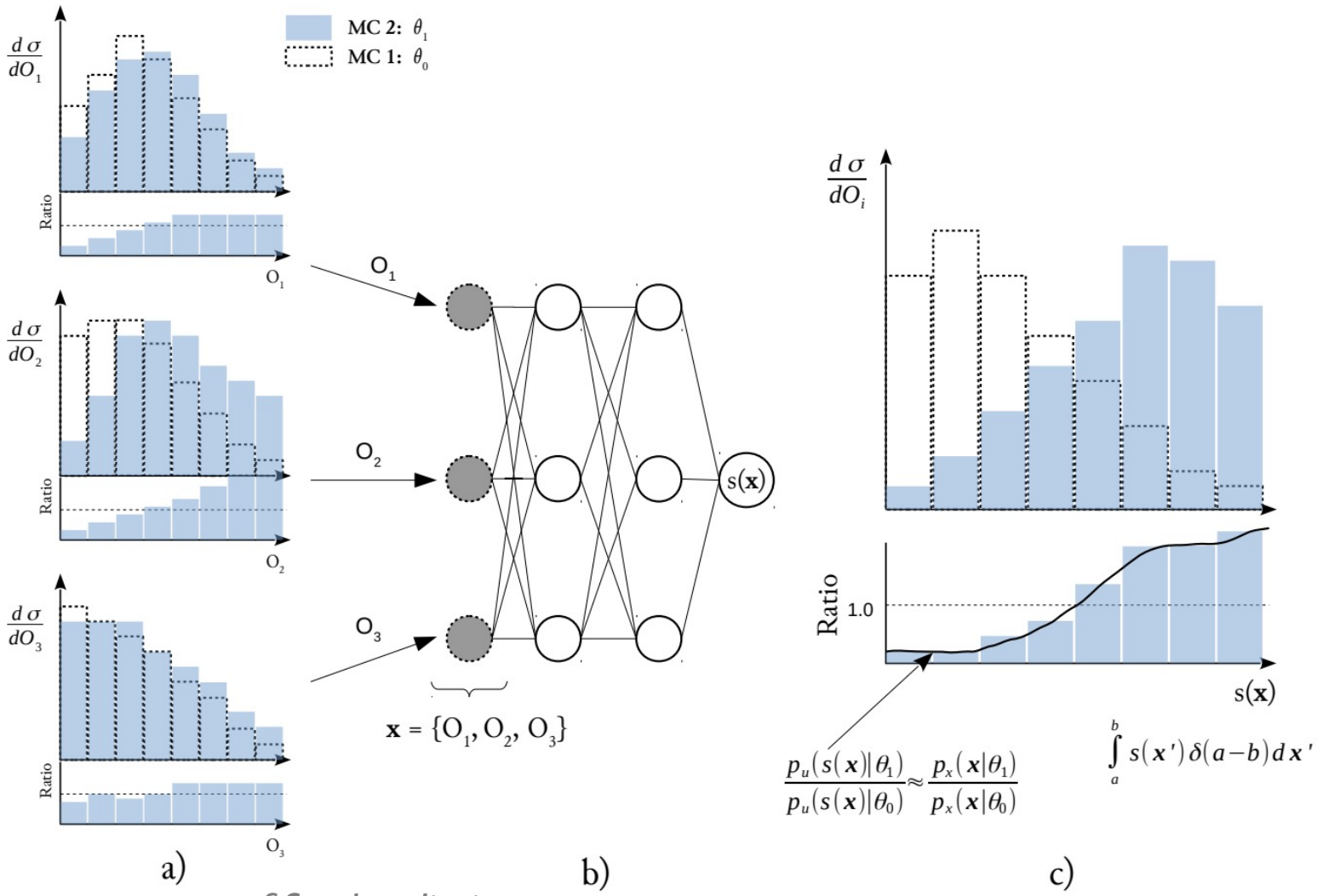


Diagram courtesy of Stephen Jiggins

BDTr approach:

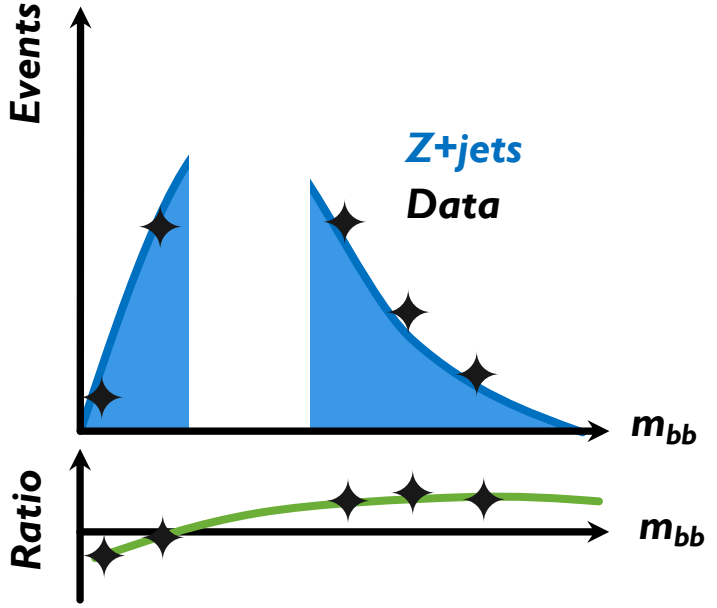
1. Train BDT classifier to separate nominal and alternative MC model
2. Evaluate classifier response for both MC models
3. Parametrise ratio of classifier response for both models
4. Reweight nominal MC by parametrisation and use as systematic uncertainty

For W+jets in VH(bb), factorise p_T^V as independent shape variation due its importance in the categorisation

Data-driven approach for Z+jets

- Use data-driven approach for Z+jets modelling in VH(bb), due to high purity of 2-lepton channel
- Sum SR+CR and subtract data-driven ttbar estimate from templates and data
- Parametrise the data/MC ratio for the m_{bb} and p_T^V distributions, while excluding m_{bb} [80,140] GeV (to remove VH and Diboson)

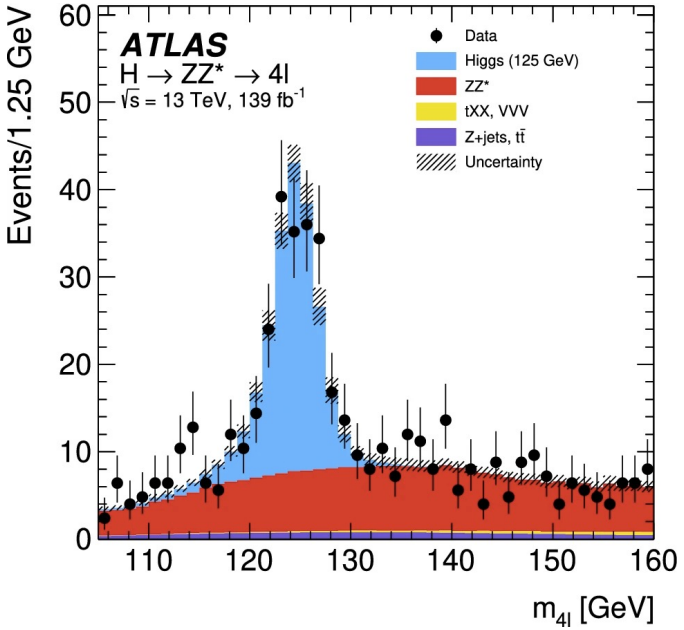
→ Use parametrised ratio as the uncertainty

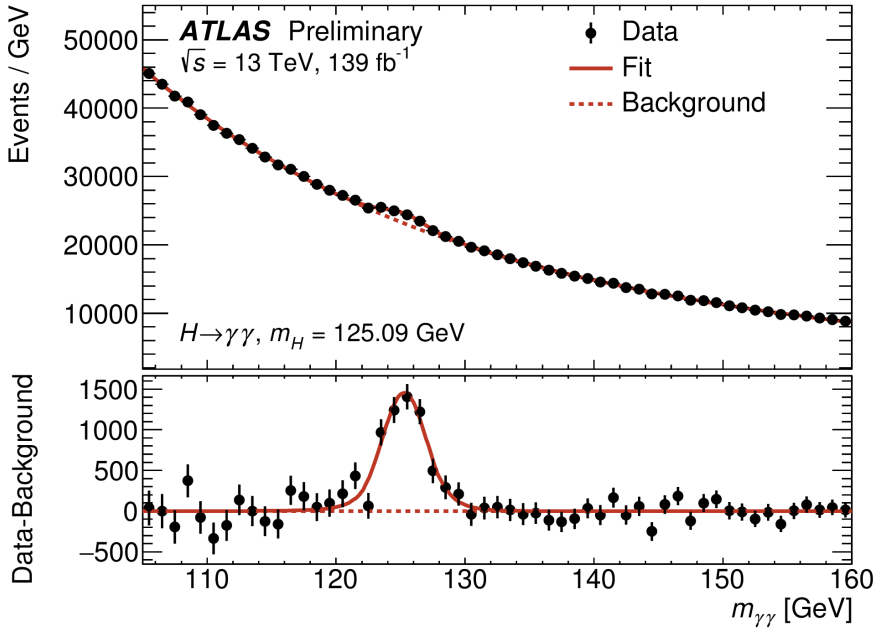


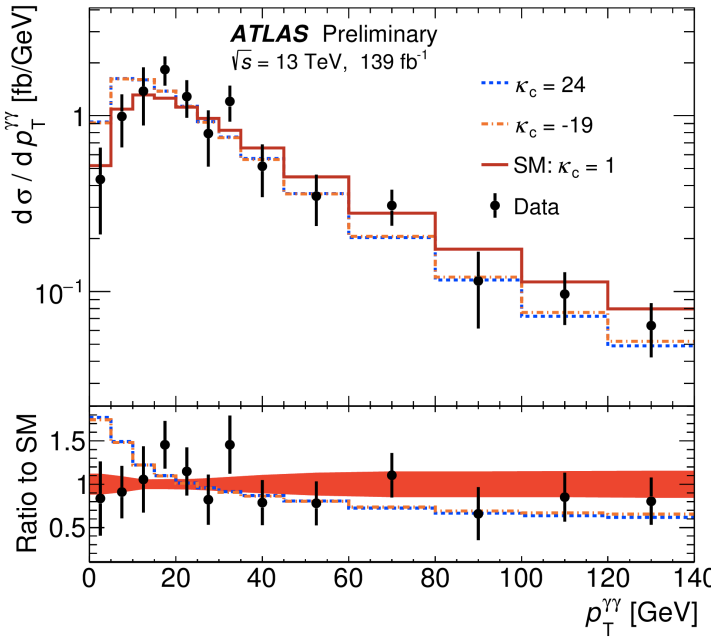
Precision measurements

- High-precision Higgs measurements in the $H\to\gamma\gamma$ and $H\to ZZ^*\to 4l$ channels
- Fit to invariant mass $m_{\gamma\gamma}$ or m_{4l}
- Inclusive and differential cross-section measurements
- $H\to\gamma\gamma$ and $H\to ZZ^*\to 4l$ 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







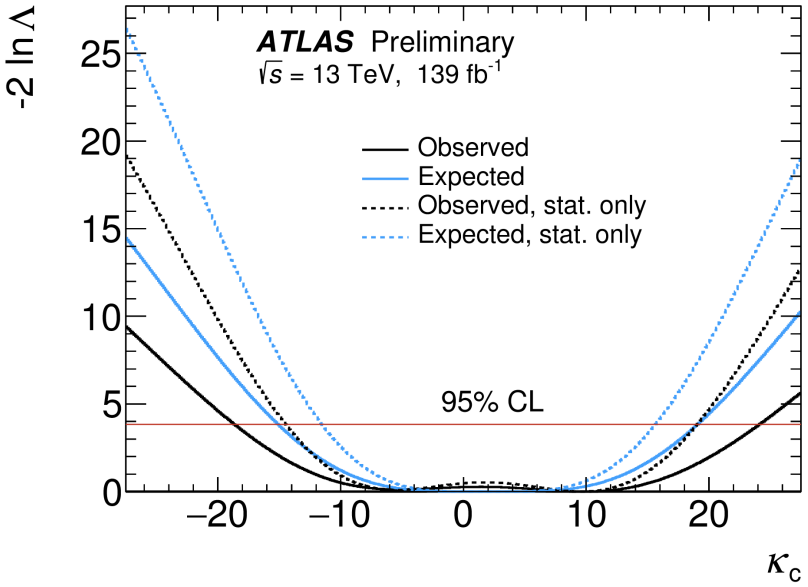
Indirect constraints

- $H\to\gamma\gamma$: 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

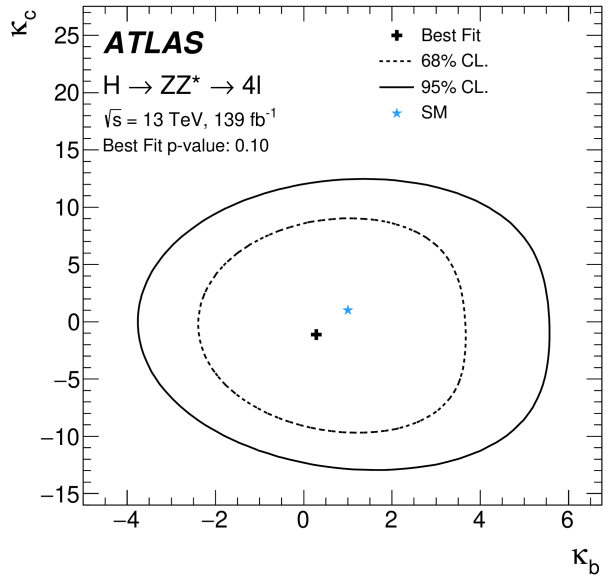
→ Limitations are complementary to H→cc, excellent pairing towards constraining the Hcc coupling with ATLAS data

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



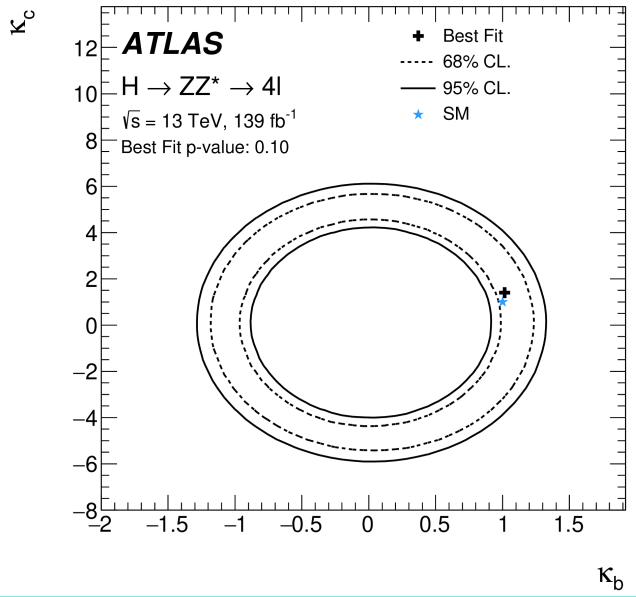
$-19 < \kappa_c < 24$

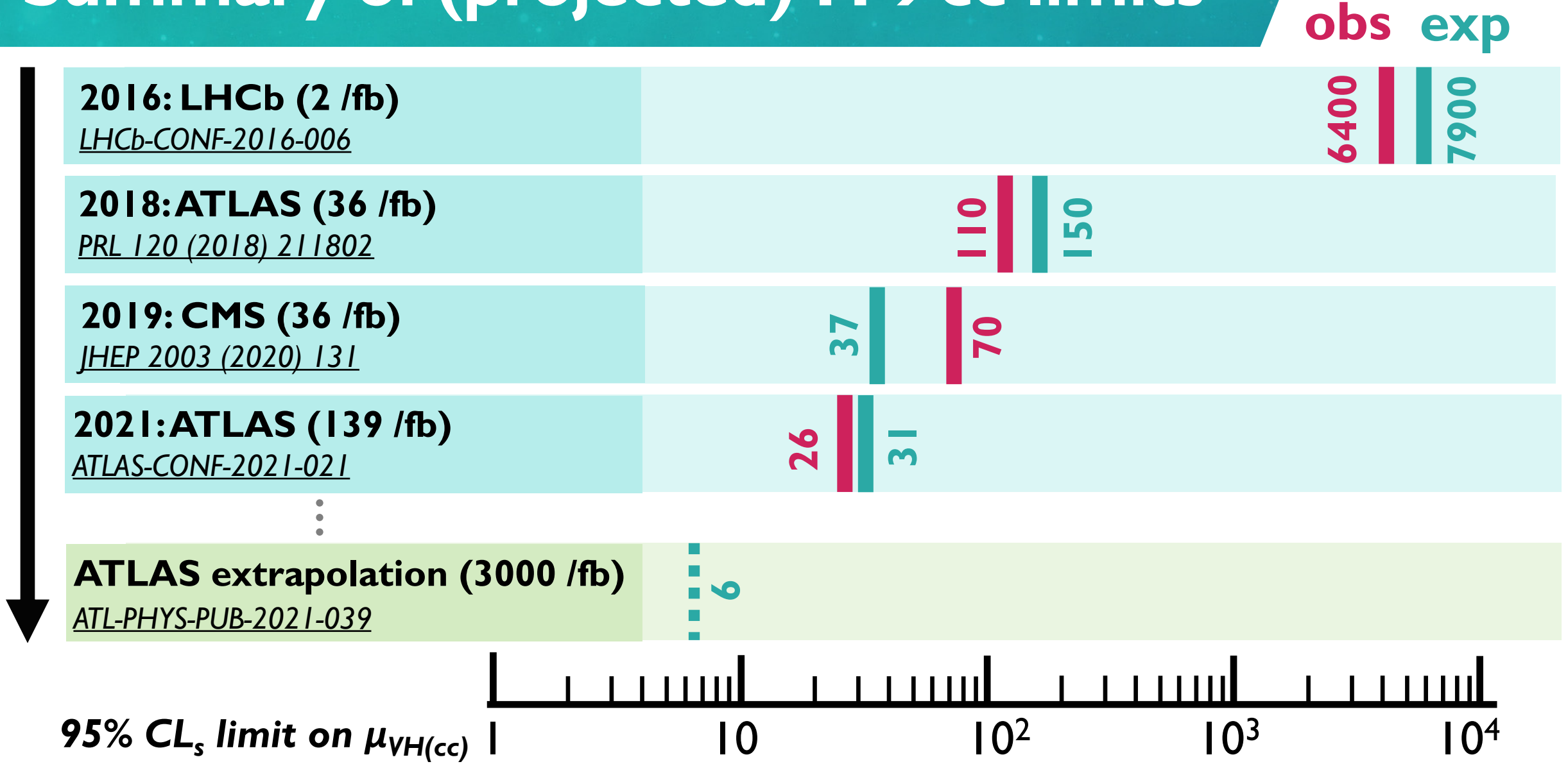
$H\to ZZ^* \to 4l$, p_T^H shape-only



$-11.7 < \kappa_c < 10.5$

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



$-7.5 < \kappa_c < 9.4$

Summary of (projected) H→cc limits