Simultaneous Measurements of VH, H→bb/cc process using ATLAS detector

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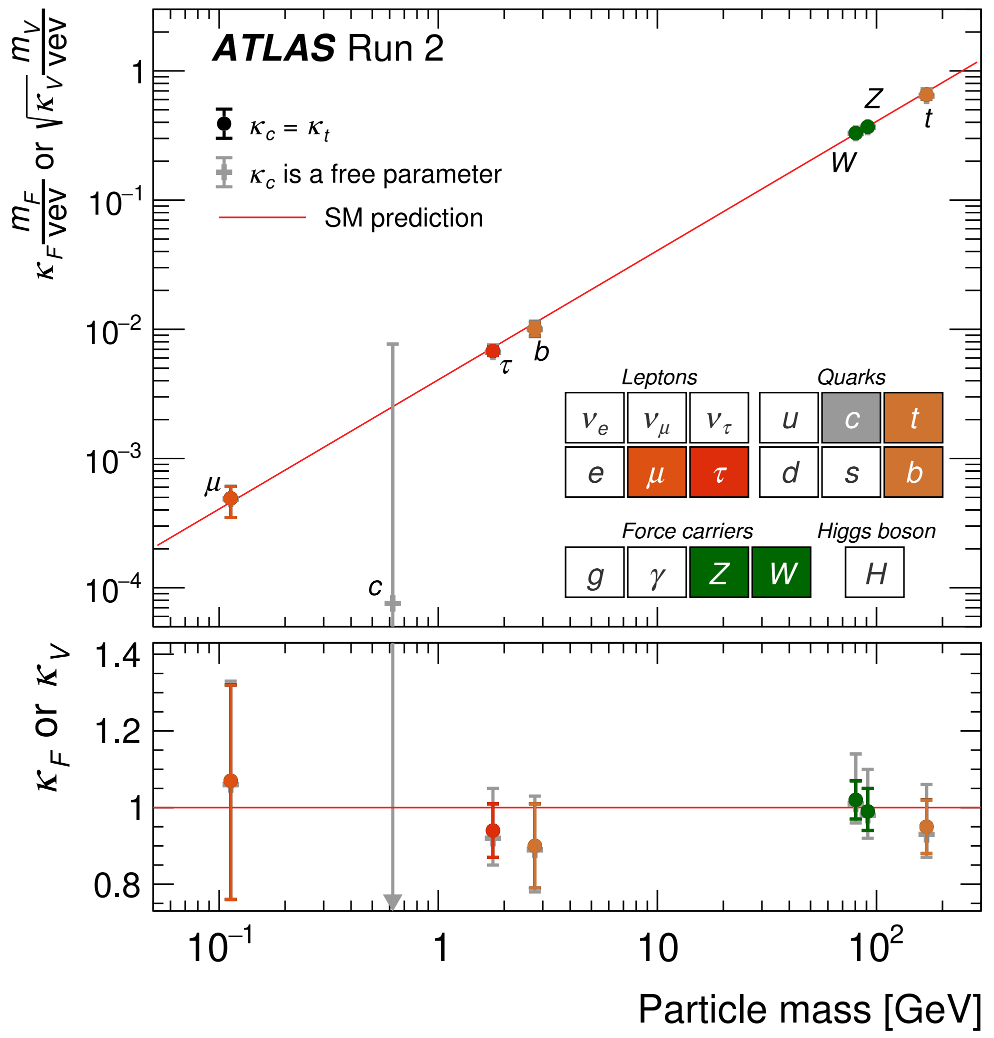
Introduction

- The measurement of Higgs Yukawa coupling is a focus of ATLAS experiments
  - Important to understand the mass generation of fermions
  - Coupling strength is predicted to be proportional to the fermion mass=> Any deviation will be a sign of new physics!

- Higgs-bottom coupling:
  - Dominant Higgs decay channel, BR($H \rightarrow bb$)~58%
  - First confirmed in VH production channel, now measured with precision around 10%

- Higgs-charm coupling
  - Largest undiscovered decay channel, BR($H \rightarrow cc$)~3%



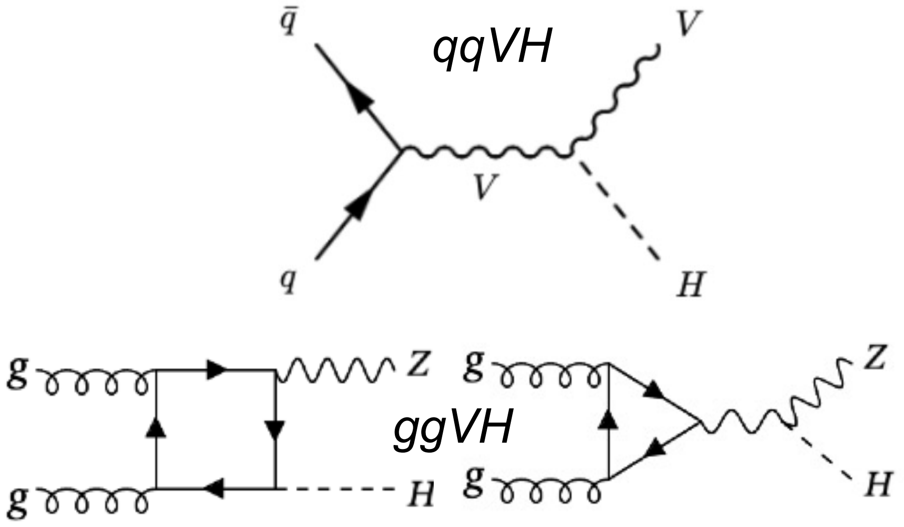
Introduction

- The Large multijet background at LHC makes the measurement of bb/cc final state very challenging

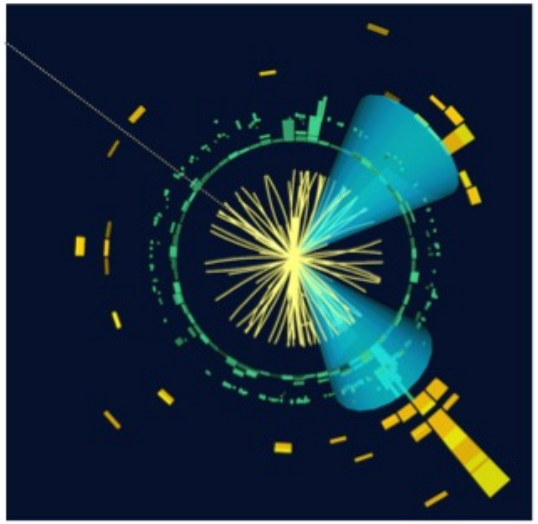
=>The vector boson associated Higgs (VH) production mode is used

  - By requiring the leptonic decay vector boson, the QCD background can be greatly suppressed
  - The most sensitive production mode for H(bb/cc) measurements

- Three vector boson decay channels targeted

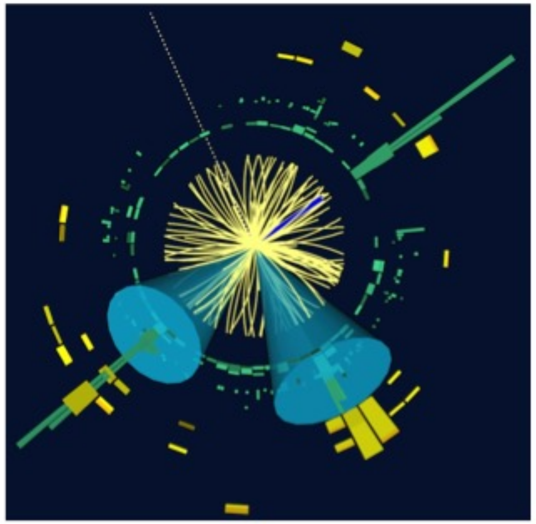


$Z(\nu\nu)H$



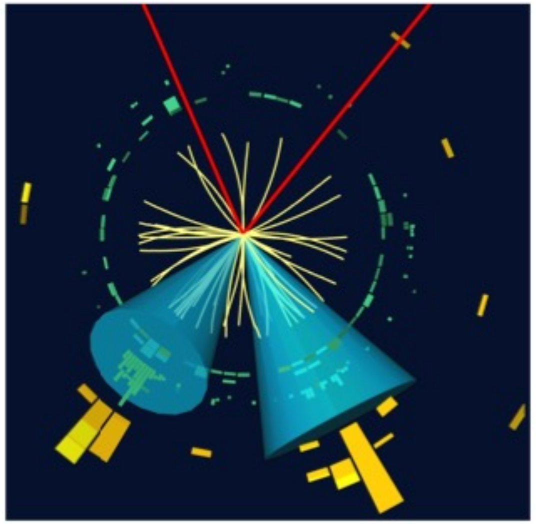
0-lepton

$W(l\nu)H$



1-lepton

$Z(ll)H$

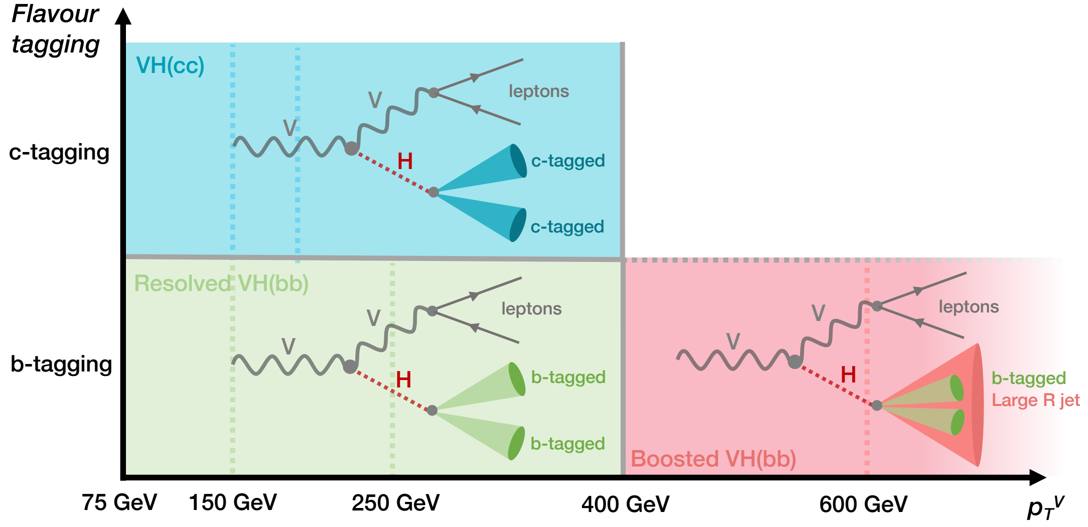


2-lepton

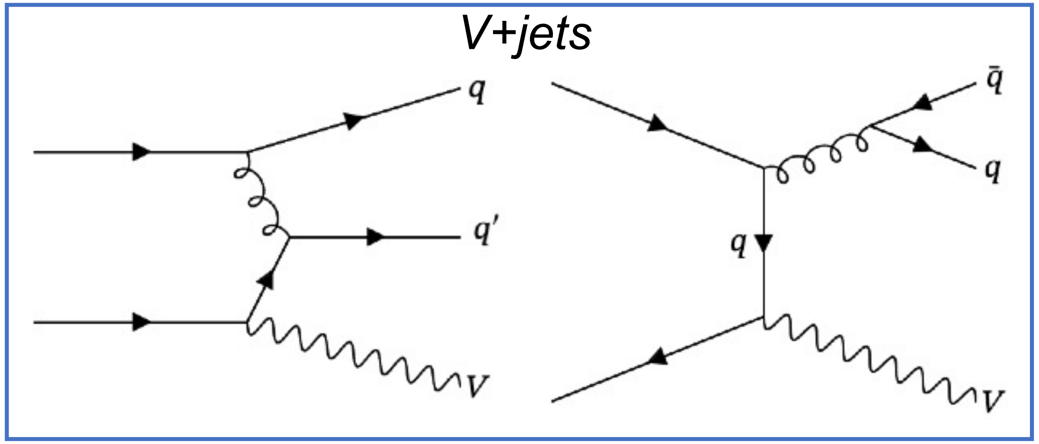
Combined Analysis

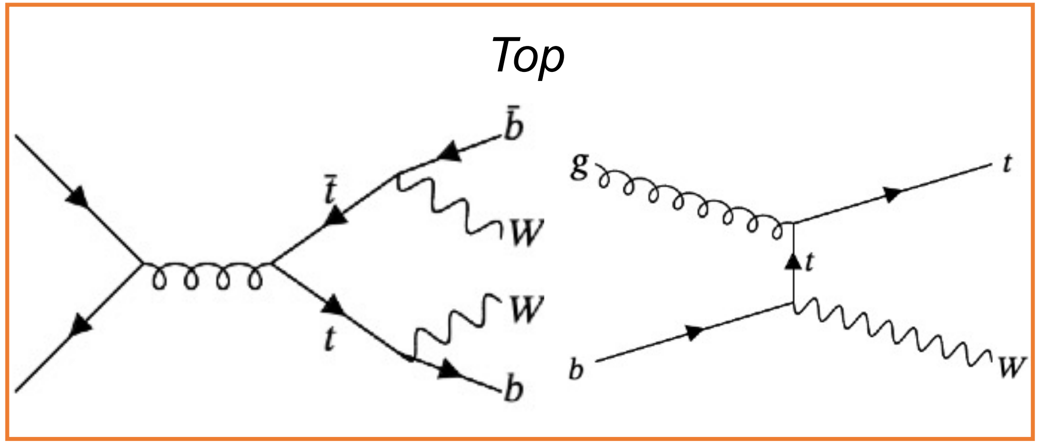
- In this ATLAS Run-2 legacy analysis, the VHbb and VHcc are combined
  - They share similar event topology and background

    =>Coherent treatment to improve the control of background
  - Extend physics output, such as simultaneous constraint on κ_b and κ_c
- VHbb resolved+boosted (split at $p_T^V = 400$ GeV), VHcc resolved



Major Background

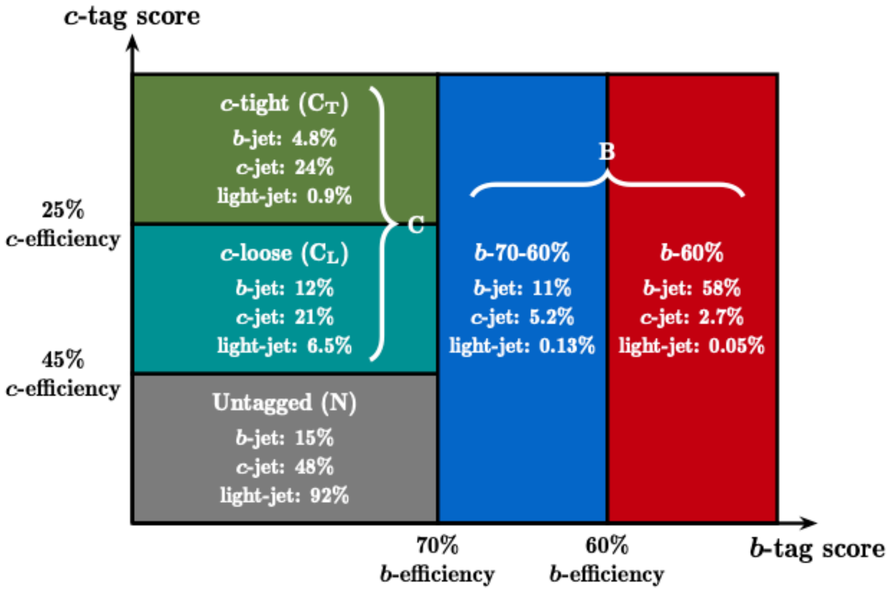




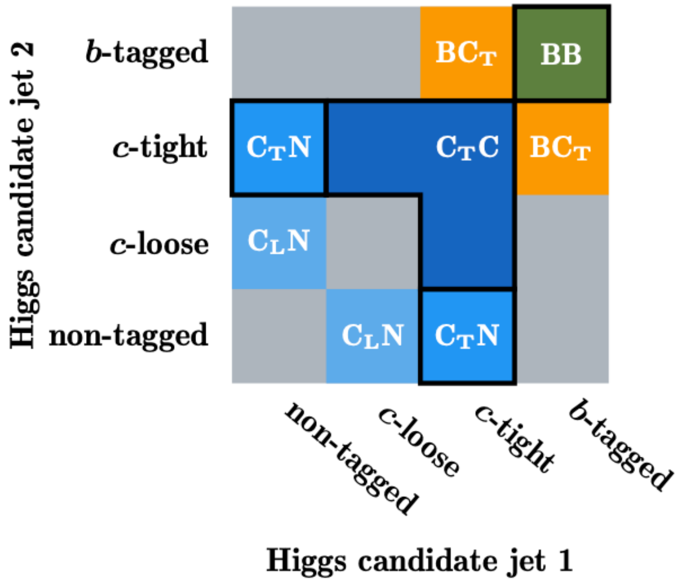
[arxiv:2410.19611](https://arxiv.org/abs/2410.19611)

Flavor Tagging Scheme

- DL1r based *b*+*c* 2D Pseudo Continuous Flavor Tagging
  - B-tag WP follows the FTAG recommendation
  - C-tag WP optimized for analysis
  - Orthogonal between b-tag and c-tag

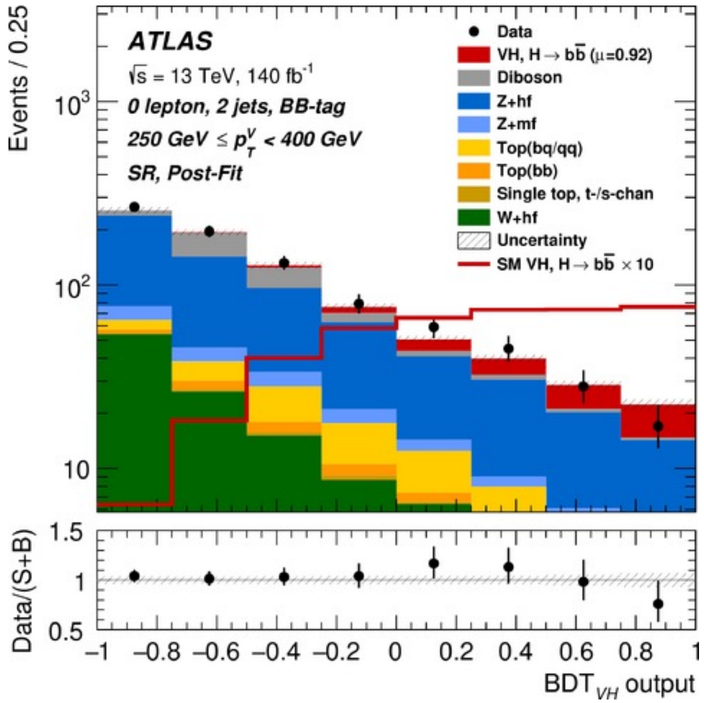


- Tag information used as region requirements
  - VHbb Enriched: Exactly two B-tag jets (BB)
  - VHcc Enriched: At least one tight c-tag ($C_TC + C_TN$)
  - Top Enriched: One B-tag and one tight c-tag (BC_T)
  - V+light Enriched: One loose c-tag and one not tagged (C_TN)

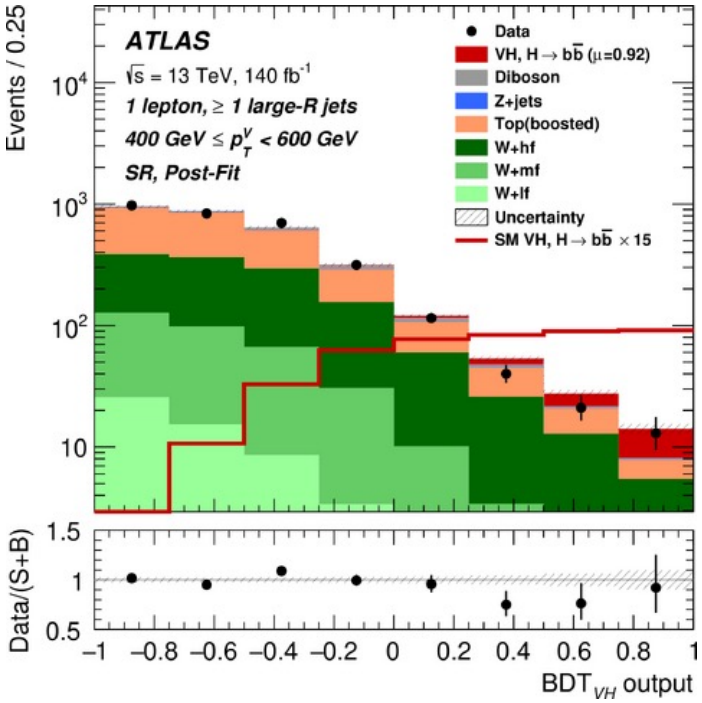


Signal Background Separation

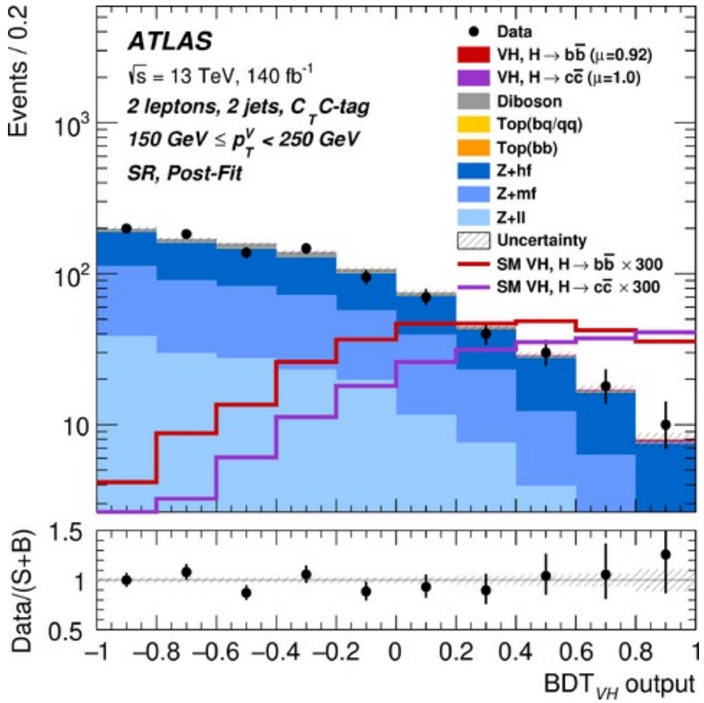
- Boosted Decision Tree (BDT) is used for signal-background classification
  - Separate training for VHcc and VHbb (First time in ATLAS use Machine Learning classifiers for VHcc and boosted VHbb)
  - VHcc significance improved by ~40%, boosted VHbb improved by ~50% compared to mass based discriminant



0-lepton Resolved VHbb



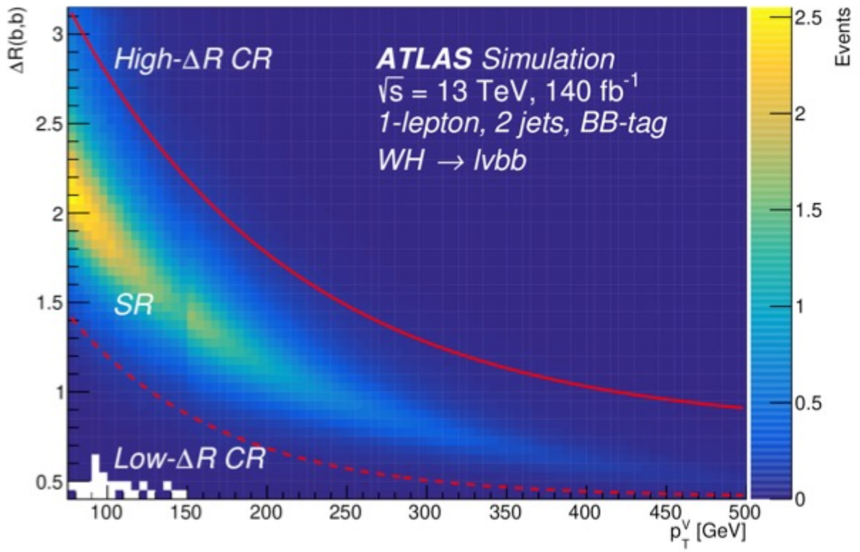
1-lepton Boosted VHbb



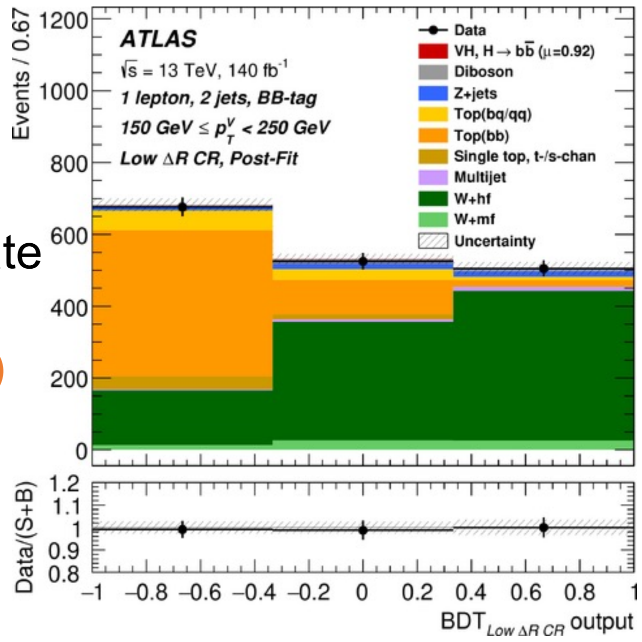
2-lepton Resolved VHcc

Control Regions: ΔR based CRs

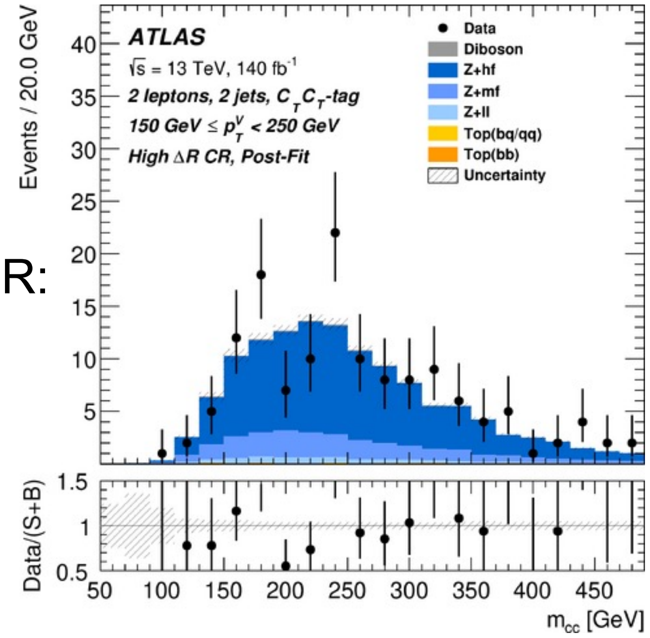
- ΔR based CRs: Control background that have same flavor as SRs
  - The ΔR sidebands are defined as a function of p_T^V, optimized with different jet multiplicity



1-lepton VHbb Low ΔR CR:
Specially trained BDT to separate W+hf from other backgrounds
Simultaneous control of Top(bb) and W+hf



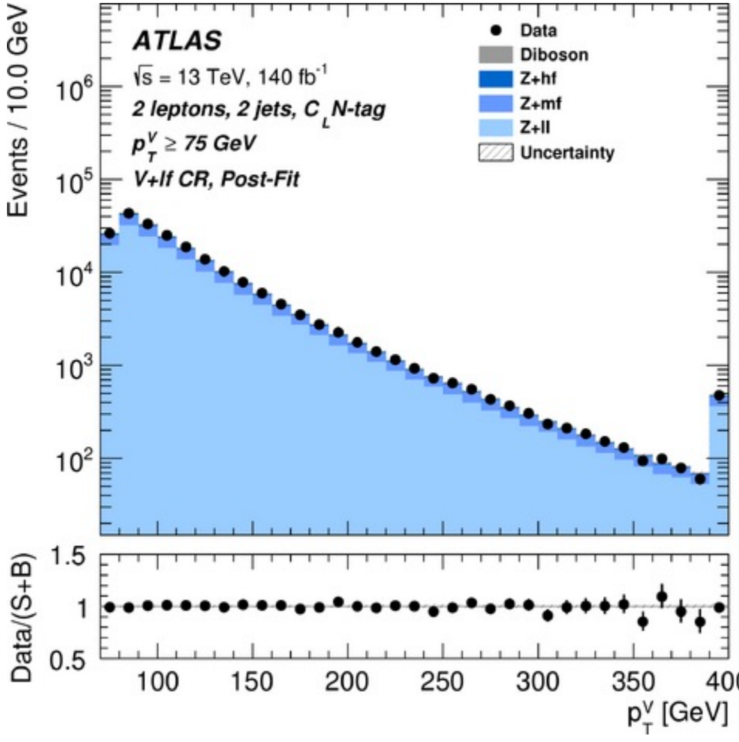
2-lepton VHcc High ΔR CR:
Control the Z+cc



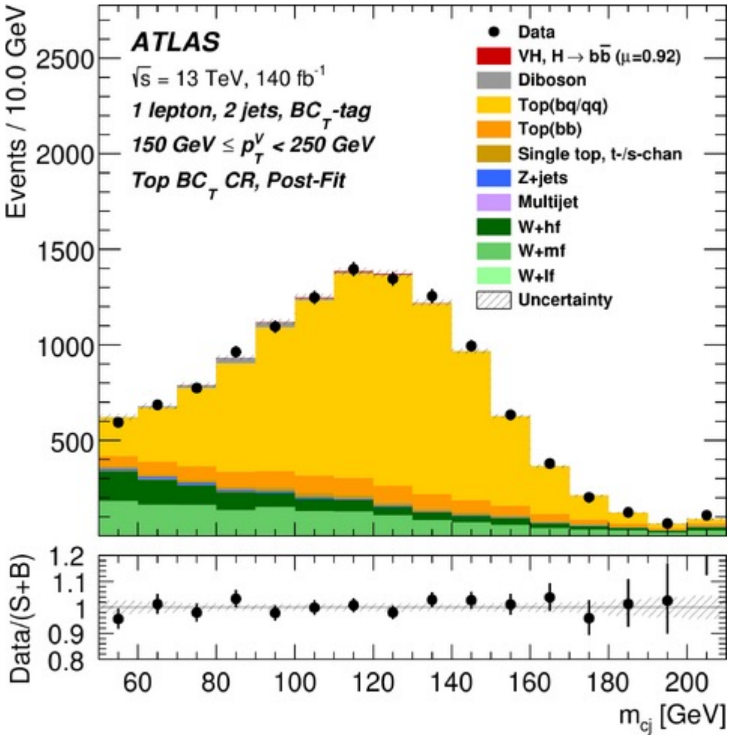
Control Regions: Tag based CRs

- Tag based CRs: Control the background that have different flavor

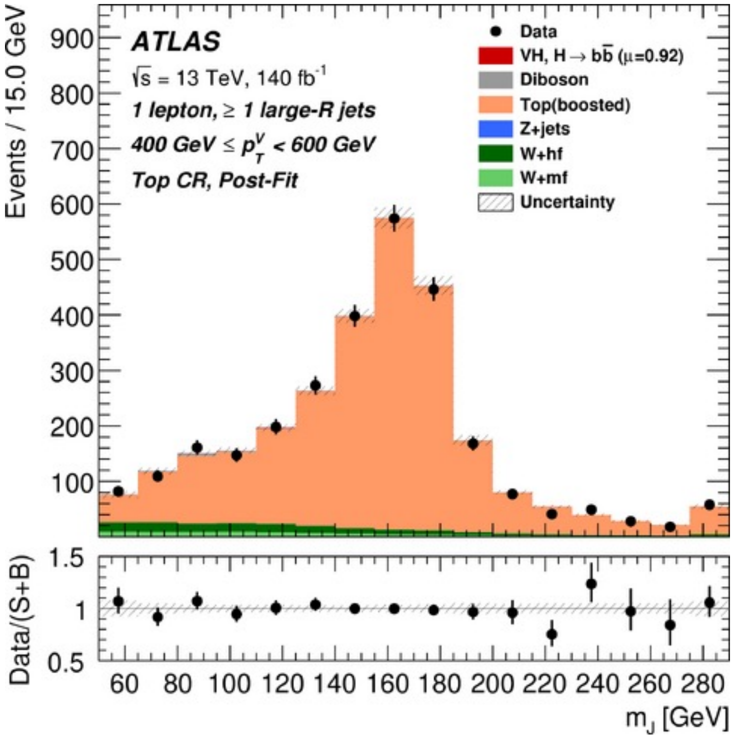
2-lepton $C_L N$ CR: Z+lf



1-lepton BC_T CR: Top(bc)



1-lepton Boosted additional b-jet CR: Top



The CRs are shared between VHbb and VHcc, ensure a good control of minor backgrounds, e.g. the V+lf in VHbb or Topbb in VHcc

VH, H→bb/cc Results

- The fit is always performed with VHbb & VHcc SRs+CRs all included, signal strength free floating
  - In total of 59 signal regions and 97 control regions
- Inclusive signal strength:

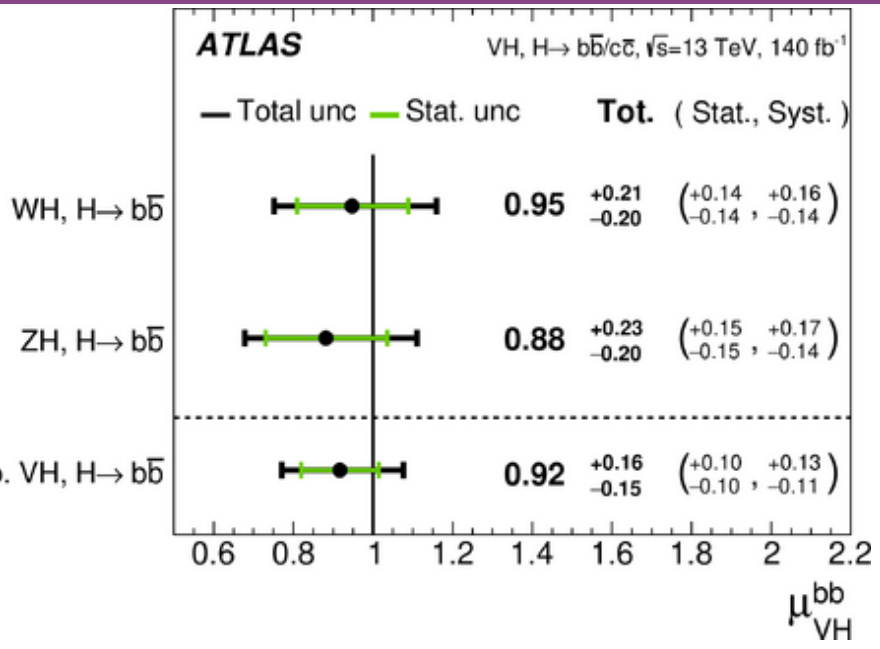
$$\mu_{VH}^{bb} = 0.92^{+0.16}_{-0.15} = 0.92 \pm 0.10\,(\text{stat.})^{+0.13}_{-0.11}\,(\text{syst.}),$$
$$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.7}_{-3.5}\,(\text{syst.}).$$

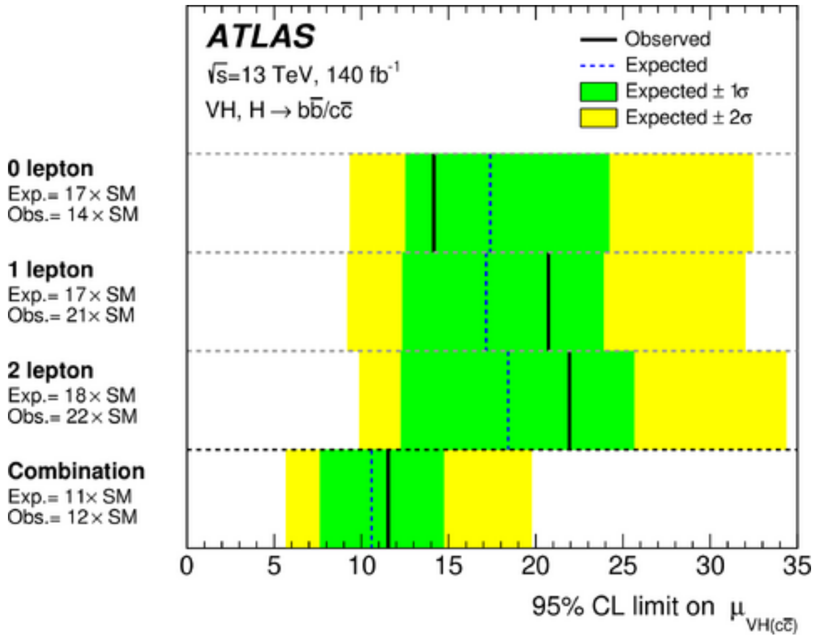
Good agreement with SM!

- First observation of WH, H→bb process with 5.3σ!
  - Compared with last ATLAS results, 23% (10%) improvement for WH (ZH)
- The VHcc upper limit is 11.5(10.6) ×SM, best observed results!
  - 3 times better than first full Run2 results
  - Mostly coming from the optimized flavor tagging scheme and BDT, also benefit from better background control

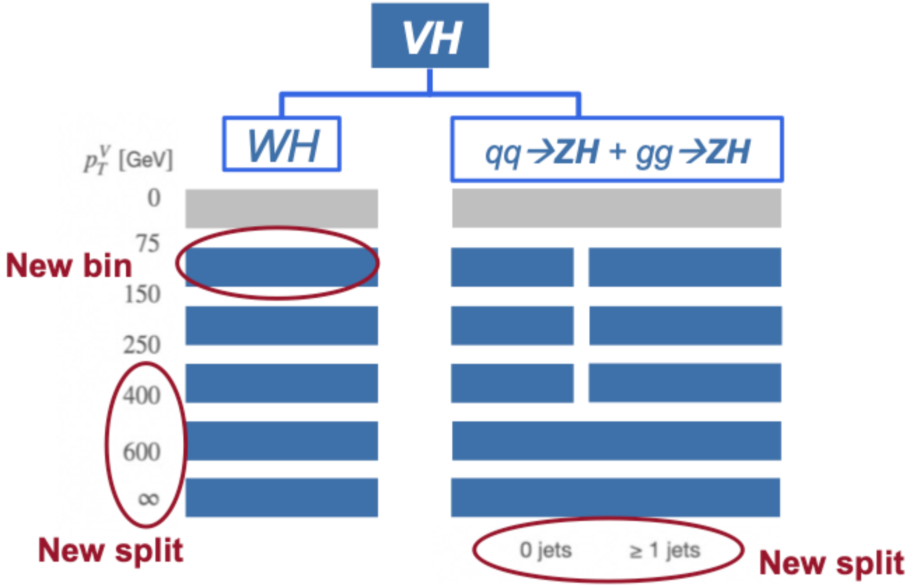
5.3(5.5)σ

4.9(5.6)σ

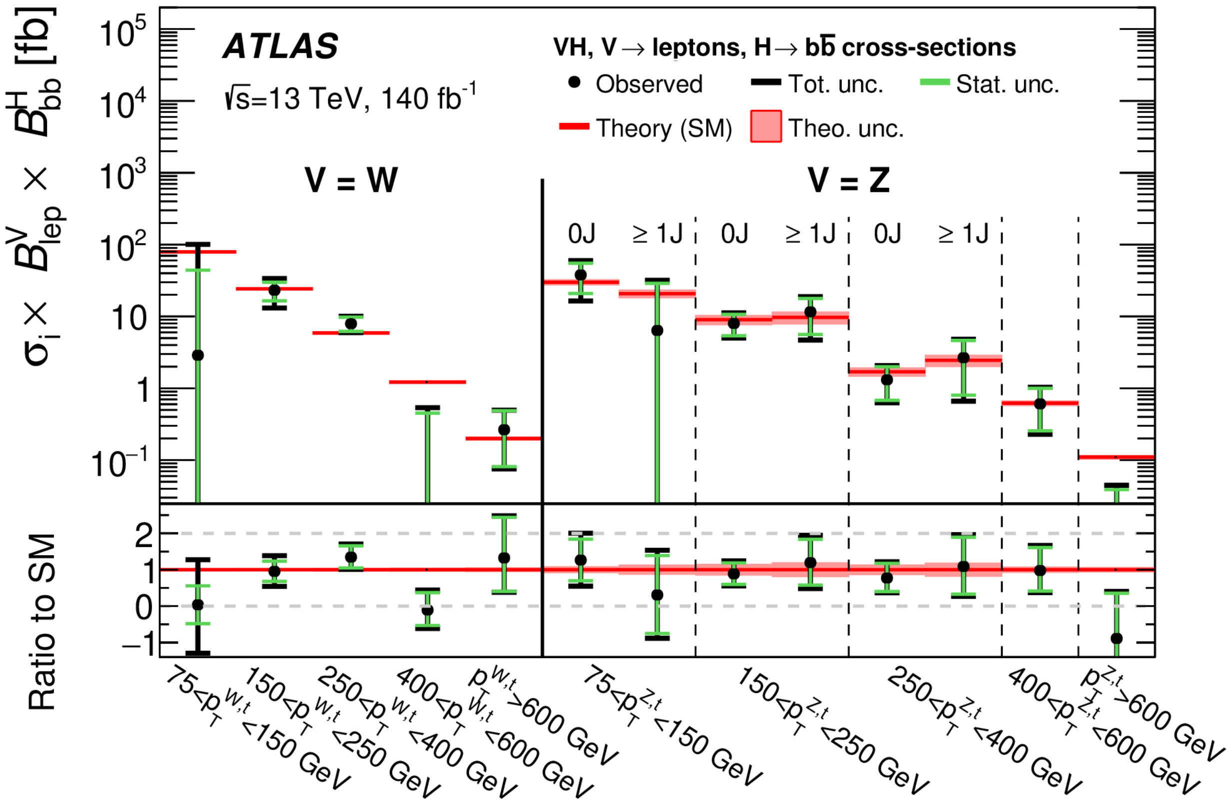




VH, H→bb/cc Results



- VH, H→bb STXS measurements
  - The analysis is designed to align with the STXS split
    - Phase spaces split in p_T^V and $N_{add.jet}$
    - Several techniques to reduce the STXS migration (FSR recovery, high additional jet pT cut…)



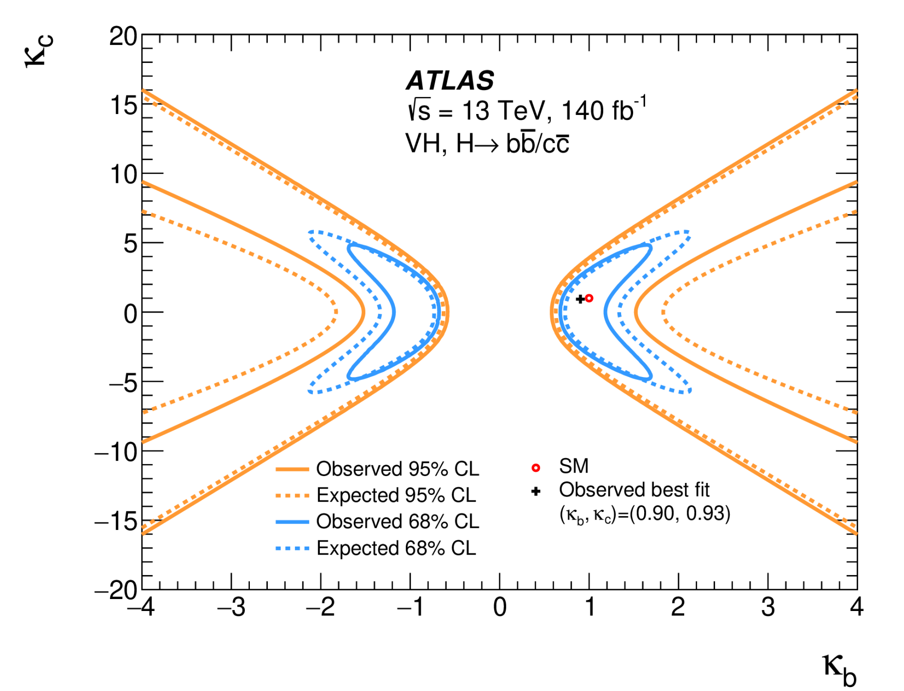
Compatibility with SM: 90%

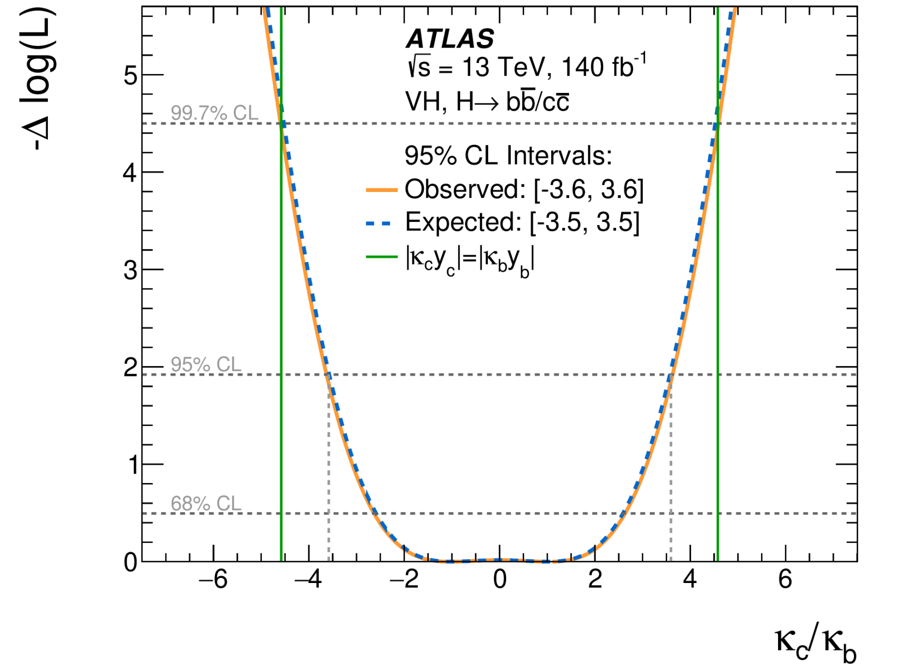
Significantly improved compared to previous results:

- Much more STXS bins: 7 → 13
- ~25% improvement in resolved bins
- Up to 50% improvement in boosted bins

VH, H→bb/cc Results

- Kappa interpretation:
  - Constraint on κ_c (with VHbb signal strength floating) : $|\kappa_c| < 4.2$ at 95% CL
  - 2D scan with κ_b and κ_c floating
  - Constraint on κ_c/κ_b:
    - $|\kappa_c/\kappa_b| < 3.6$ at 95% CL
    - $|\kappa_c/\kappa_b| < 4.578$ at 99.7% CL => Higgs-bottom coupling is stronger than the Higgs-charm coupling at ~3σ





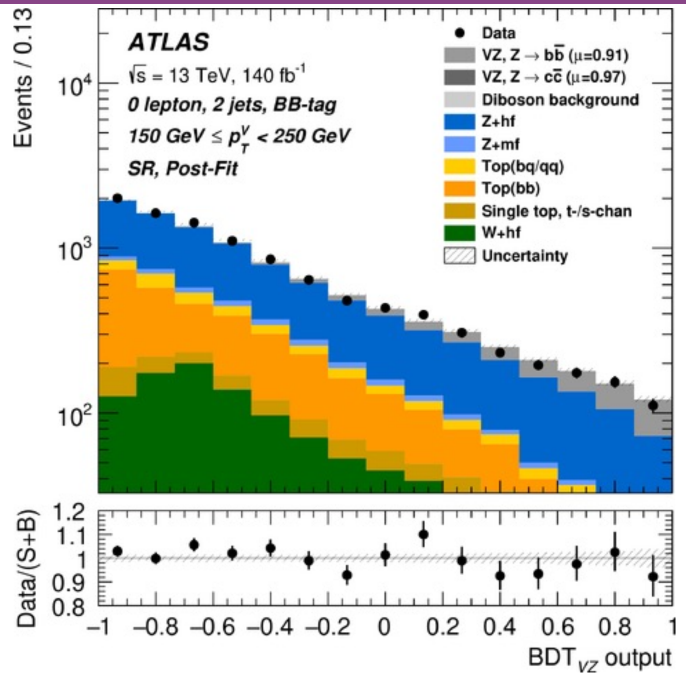
VZ, Z →bb/cc Cross-check

- VZbbcc topology is very similar with VHbbcc, but with larger cross-section, the VZ process is used as a cross-check
  - To validate the BDT and analysis strategy
  - Specific BDT is trained using VZ as signal, other settings exact same as VH
  - Fit models same as VH
- Signal strength:

$$\mu_{VZ}^{bb} = 0.92^{+0.13}_{-0.11}$$

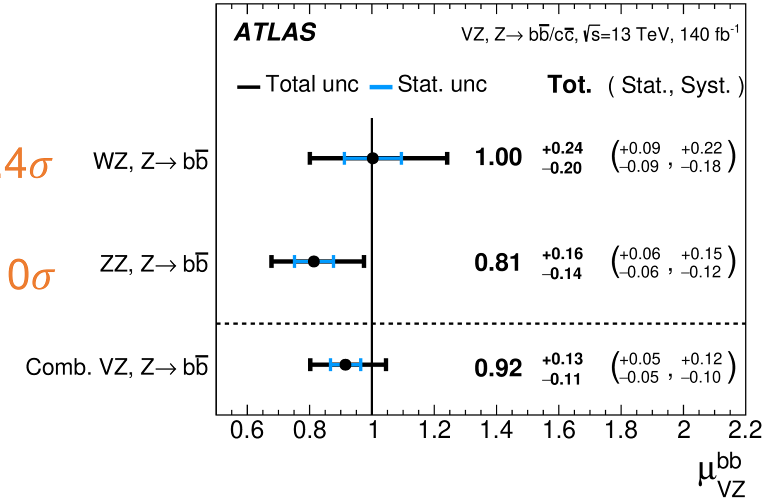
$$\mu_{VZ}^{cc} = 0.98^{+0.25}_{-0.22}$$

- **VZ, Z →cc process is observed with 5.2σ!**



6.4σ

>10σ



Summary

- ATLAS has performed the simultaneous measurement of VH, H→bb/cc process using full Run-2 dataset
  - Custom DL1r based 2D Pseudo Continuous Flavor tagging, optimized c-tagging performance, orthogonal between b- and c-tagging
  - BDT used for signal-background classification, brings up to 50% improvement
  - Coherent treatment of background, specially designed tag based CRs for different flavor components
- Significant improvements compared to previous results
  - **First observation of WH(bb)** and WZ(bb), first observation of VZ(cc) at ATLAS
  - STXS VHbb measurements in more granular, uncertainties improved up to 50%
  - **Best observed VH(cc) upper limit**, $\mu_{VH}^{cc} < 11.3 \times$SM @ 95% CL
  - Higgs-bottom coupling is observed to be stronger than the Higgs-charm coupling at ~3σ

Backup

Higgs mass corrections

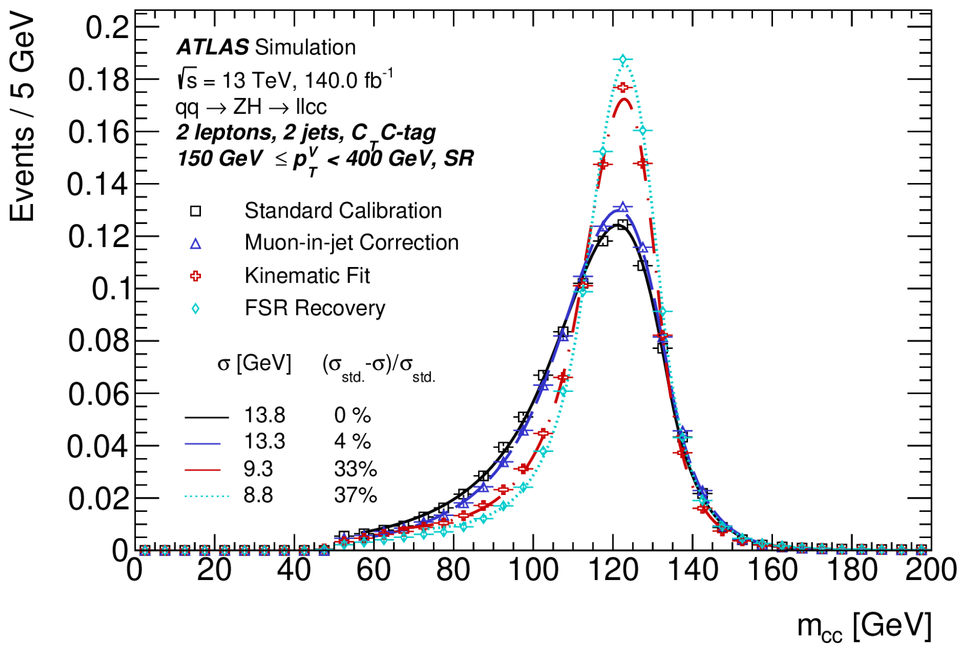
- Improvement of higgs mass resolution:
  - **muon-in-jet correction** and **PtReco**
  - **Kinematic Fit**: Balance the pT of leptons and jets from Higgs decay applied

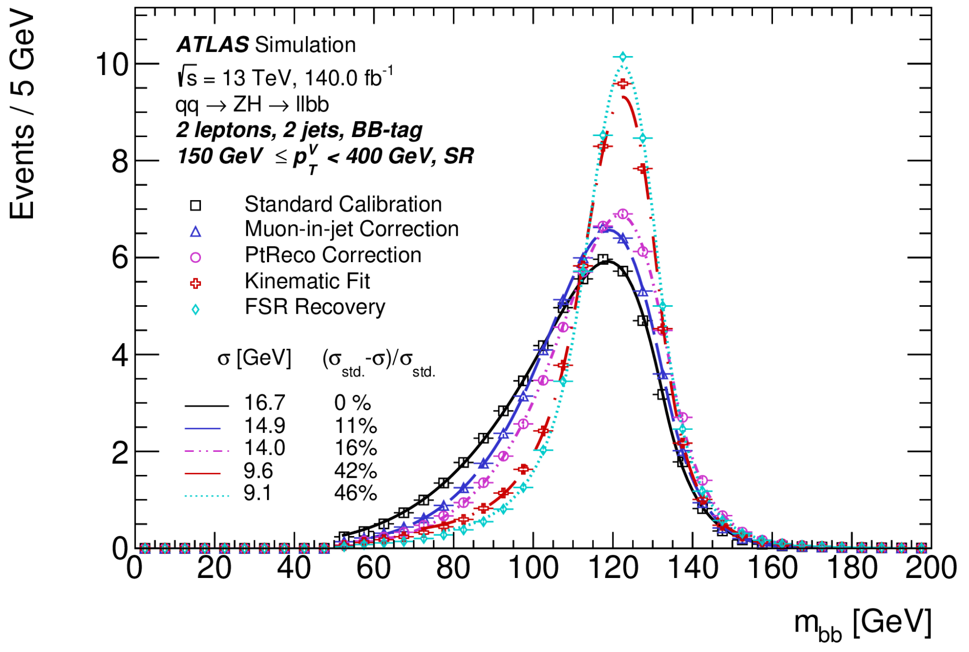
$$-2\ln L = -\sum_{\text{jet}} 2\ln \mathcal{L}(p_T, p_T^{\text{Fit}}) + \sum_{\text{leptons}} \frac{\left(p_{\text{T}}^{\text{Nominal}} - p_{\text{T}}^{\text{Fit}}\right)^2}{\sigma_{p_{\text{T}}^2}} + \frac{\left(p_{\text{X}}^{ZH}\right)^2}{\sigma^2_{p_{\text{X}}^{ZH}}} + \frac{\left(p_{\text{X}}^{ZH}\right)^2}{\sigma^2_{p_{\text{Y}}^{ZH}}} + 2\ln\left((m_{ll}^2 - m_Z^2)^2 + m_Z^2\Gamma_Z^2\right)$$

  - **FSR Recovery**: 2L resolved channel only, corrects back the jet from b-jet FSR

➢Introduced Kinematic Fit to VHcc 2L for the first time

➢Harmonize the FSR and Kinematic Fit



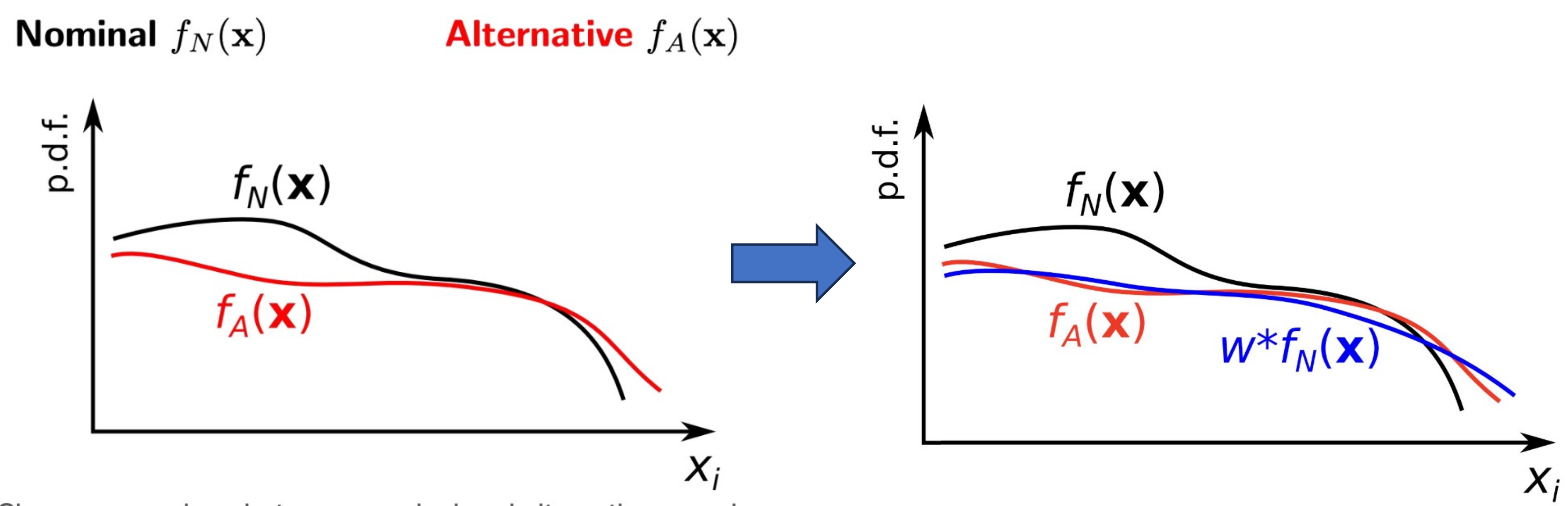


BDT Training variables

	Resolved $VH,\ H \rightarrow b\bar{b}, c\bar{c}$			Boosted $VH,\ H \rightarrow b\bar{b}$		
Variable	0-lepton	1-lepton	2-lepton	0-lepton	1-lepton	2-lepton
m_H	✓	✓	✓	✓	✓	✓
$m_{j_1 j_2 j_3}$	✓	✓	✓			
$p_{\mathrm{T}}^{j_1}$	✓	✓	✓	✓	✓	✓
$p_{\mathrm{T}}^{j_2}$	✓	✓	✓	✓	✓	✓
$p_{\mathrm{T}}^{j_3}$				✓	✓	✓
$\sum p_{\mathrm{T}}^{j_i}, i > 2$	✓	✓	✓			
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_1)$	✓	✓	✓	✓	✓	✓
$\mathrm{bin}_{D_{\mathrm{DL1r}}}(j_2)$	✓	✓	✓	✓	✓	✓
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	✓	✓	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	✓	✓
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓	✓		✓	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			✓			
$\lvert\Delta\phi(\boldsymbol{V}, \boldsymbol{H})\rvert$	✓	✓	✓	✓	✓	✓
$\lvert\Delta y(\boldsymbol{V}, \boldsymbol{H})\rvert$		✓	✓		✓	✓
$\Delta R(\boldsymbol{j_1}, \boldsymbol{j_2})$	✓	✓	✓	✓	✓	✓
$\min[\Delta R(\boldsymbol{j_i}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})], i > 2$	✓	✓				
N(track-jets in J)				✓	✓	✓
N(add. small-R jets)				✓	✓	✓
colour ring				✓	✓	✓
$\lvert\Delta\eta(\boldsymbol{j_1}, \boldsymbol{j_2})\rvert$	✓					
$H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$	✓					
m_{T}^{W}		✓				
m_{top}		✓				
$\min[\Delta\phi(\boldsymbol{\ell}, \boldsymbol{j_1} \text{ or } \boldsymbol{j_2})]$		✓				
p_{T}^{ℓ}					✓	
$(p_{\mathrm{T}}^{\ell} - E_{\mathrm{T}}^{\mathrm{miss}})/p_{\mathrm{T}}^{V}$					✓	
$m_{\ell\ell}$			✓			
$\cos\theta^*(\boldsymbol{\ell^-}, \boldsymbol{V})$			✓			✓

CARL uncertainties

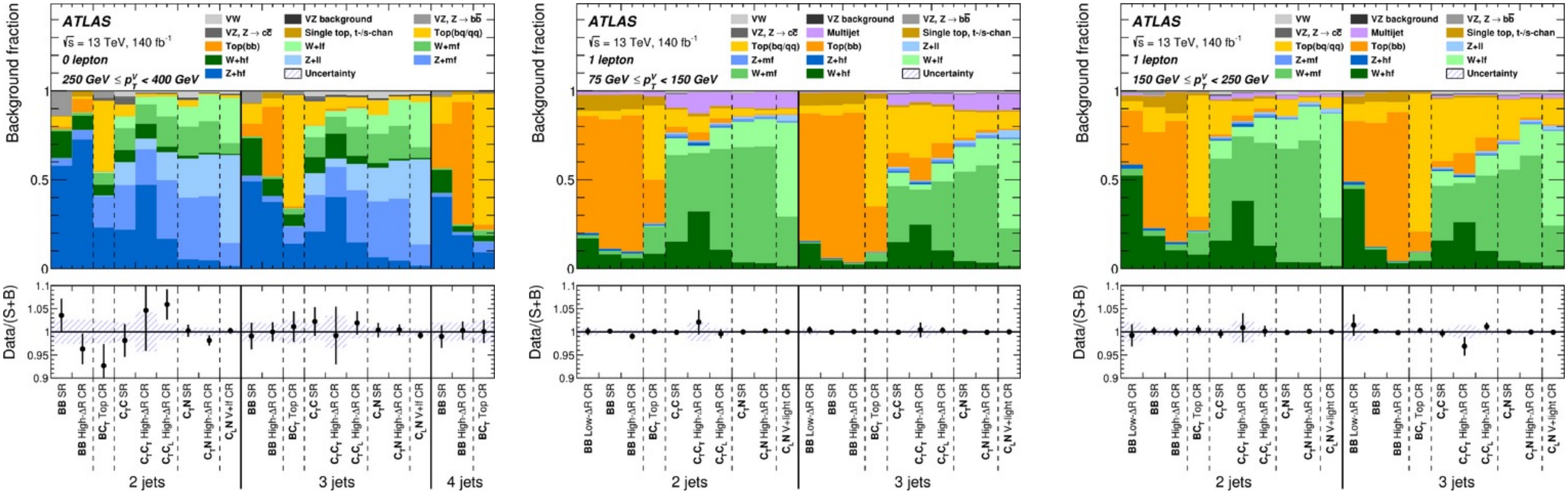
- New Modelling technique: Shape uncertainties derived with a Neural Network framework (CARL)
  - Reweight nominal events to mimic the distribution of alternative samples ⇒ Benefit from the large size of nominal sample, smoother shape uncertainties



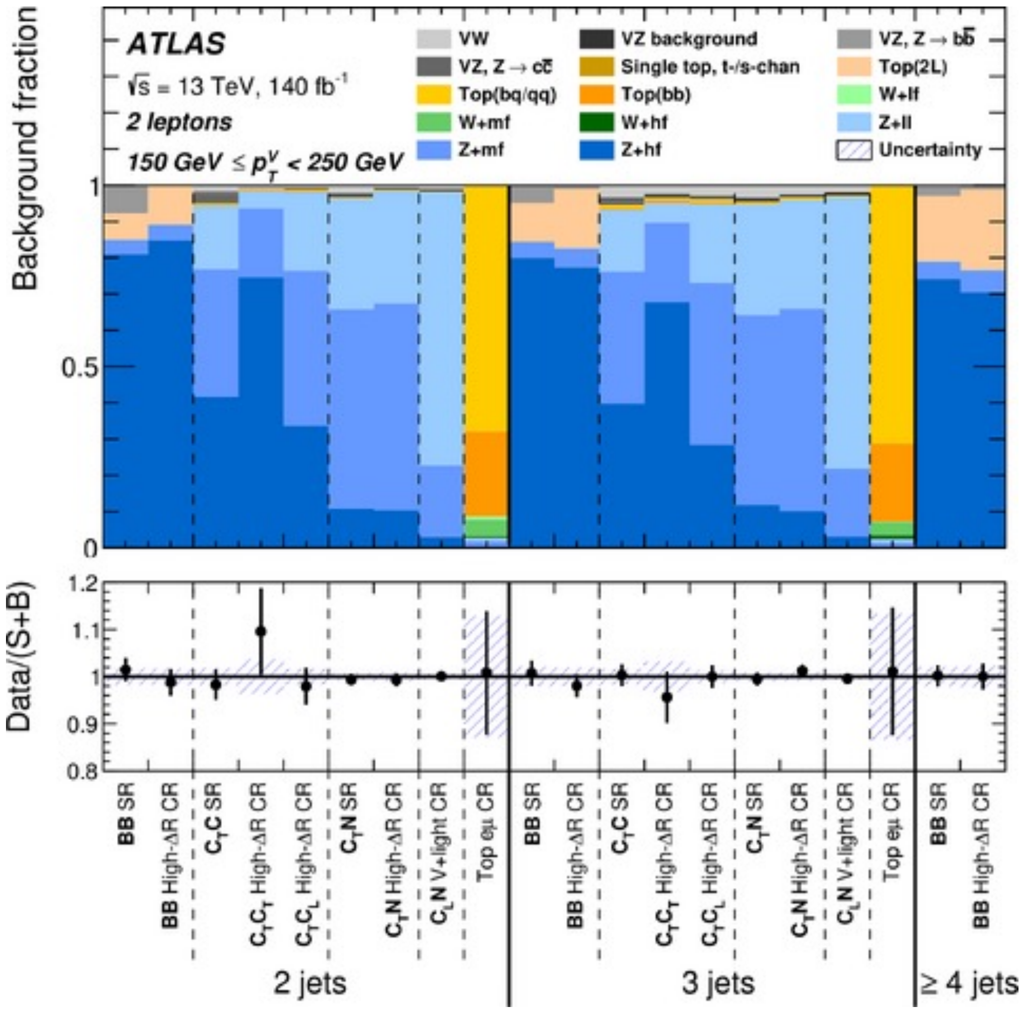
Shape comparison between nominal and alternative sample

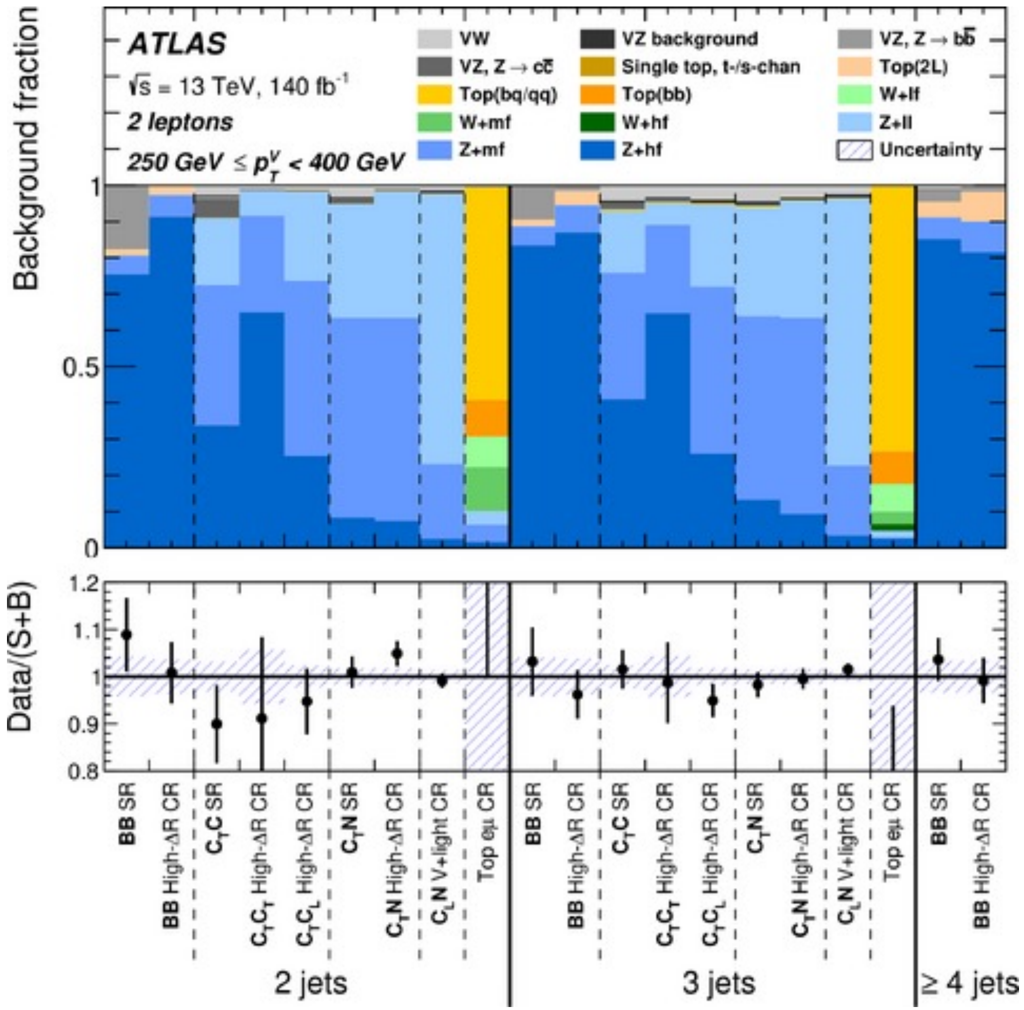
Shape comparison using CARL reweighting

Background Composition



Background Composition





Breakdown table

Source of uncertainty		σ_μ			
		$VH,\ H\to b\bar{b}$	$WH,\ H\to b\bar{b}$	$ZH,\ H\to b\bar{b}$	$VH,\ H\to c\bar{c}$
Total		0.153	0.204	0.216	5.31
Statistical		0.097	0.139	0.153	3.94
Systematic		0.118	0.149	0.153	3.57
Statistical uncertainties					
Data statistical		0.090	0.129	0.139	3.67
$t\bar{t}$ $e\mu$ control region		0.009	0.014	0.027	0.08
Background floating normalisations		0.034	0.049	0.042	1.24
Other VH floating normalisation		0.007	0.018	0.014	0.33
Simulation samples size		0.023	0.033	0.030	1.62
Experimental uncertainties					
Jets		0.027	0.035	0.030	1.02
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.010	0.005	0.021	0.23
Leptons		0.003	0.002	0.010	0.25
b-tagging	b-jets	0.020	0.018	0.026	0.29
	c-jets	0.013	0.017	0.012	0.73
	light-flavour jets	0.005	0.008	0.008	0.66
Pile-up		0.008	0.017	0.002	0.23
Luminosity		0.006	0.007	0.006	0.08
Theoretical and modelling uncertainties					
Signal		0.076	0.074	0.101	0.72
Z + jets		0.042	0.018	0.081	1.77
W + jets		0.054	0.087	0.026	1.42
$t\bar{t}$ and Wt		0.018	0.033	0.018	1.02
Single top-quark (s-, t-ch.)		0.010	0.018	0.002	0.16
Diboson		0.033	0.039	0.049	0.52
Multijet		0.005	0.010	0.005	0.55

More kappa plots