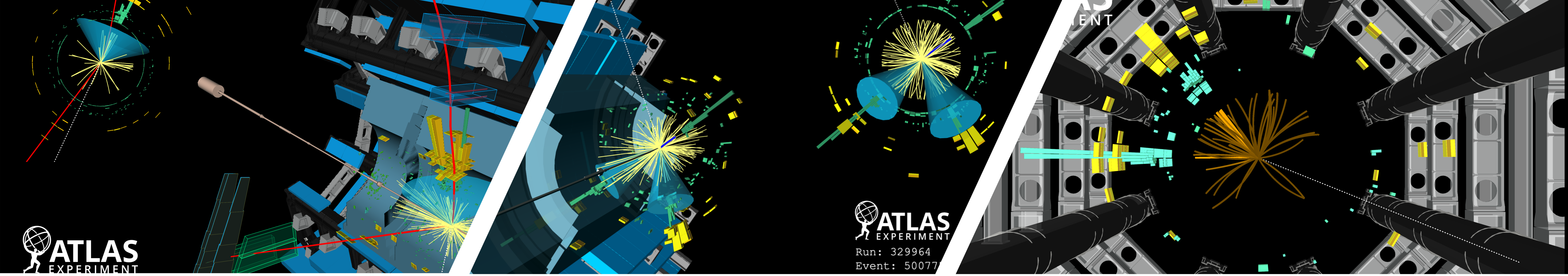


Measurements of Higgs boson coupling properties to bottom quarks and charm quarks with the ATLAS detector

Francesco Armando Di Bello, U. Di Genova and INFN
ICHEP 2024, on behalf of the ATLAS Collaboration

Università di Genova

ATLAS EXPERIMENT

INFN

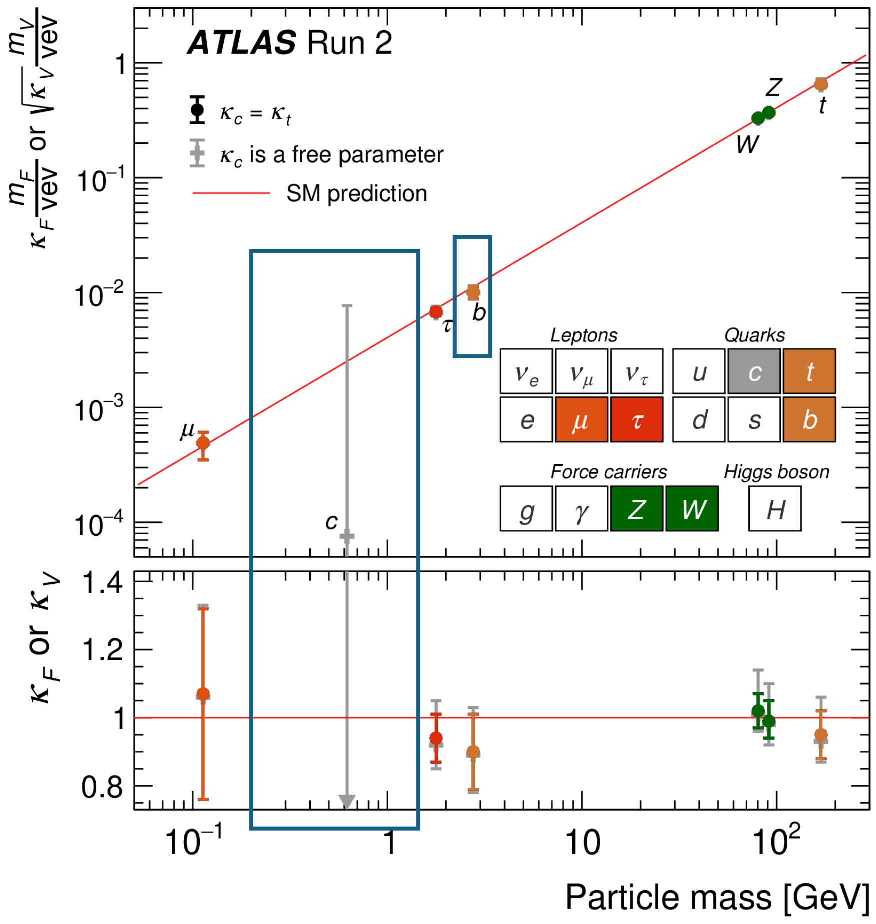
The Yukawa couplings to b- and c-quarks

- Probing the Yukawa couplings in the quark sector is a milestone for the LHC physics programme

- Measurements of the Yukawa couplings to bottom is reaching precision era!

- Growing interest from the community towards the second generation, i.e. the charm-Yukawa. Main question is: is this accessible at the LHC?

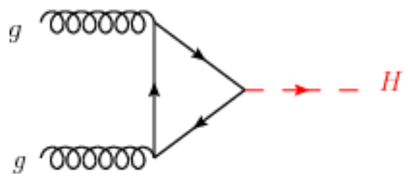
$$\mathcal{L}_{\text{fermion}} = -\underbrace{\frac{y_f v}{\sqrt{2}} \cdot \bar{\psi}\psi}_{\text{mass term}} - \underbrace{\frac{y_f}{\sqrt{2}} \cdot h\bar{\psi}\psi}_{\text{coupling term}}$$



Overview of the searches sensitive to Y_b

- A rich experimental investigation for a challenging final state
- All main production mechanisms are being studied, inclusively, differentially (STXS), fully fiducially

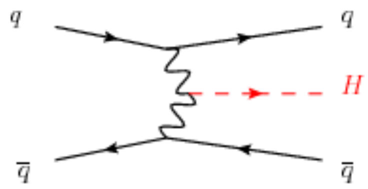
$\sigma \sim 48$ pb $\frac{S}{B} \sim 0.001$



- Dominated by QCD, needs to search at high energy (> 400 GeV)
- Sensitive to NP in the loop

PRD 105, 092003

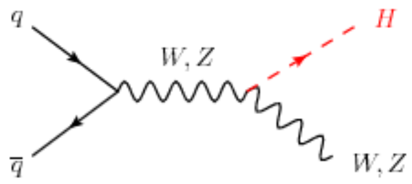
$\sigma \sim 4$ pb $\frac{S}{B} \sim 0.01$



- Exploit also channel with associated photon
- NLO EW allows to study the sign of the VH coupling

EPJC10052 2402.00426

$\sigma \sim 95$ fb $\frac{S}{B} \sim 0.1$



New for ICHEP

ATLAS-CONF-2024-010

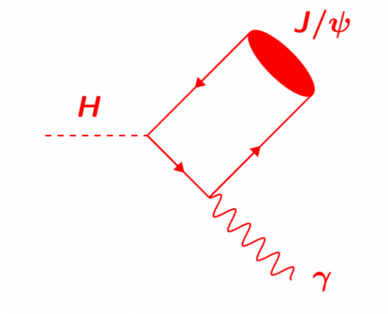
ATLAS-CONF-2022-015 PRL132.131802

*NB: tH/ttH discussed in details in a separate talk: dedicated talk

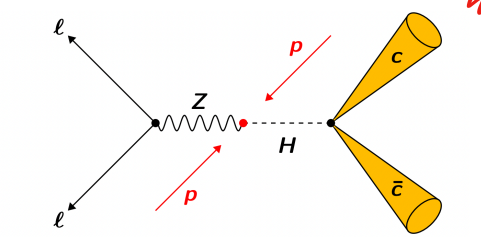
Overview of Yc constraints

- Is it possible to measure this in the lifetime of LHC?
- Complementary approaches, with different size on assumptions, needed. e.g on the presence of BSM
- Summary given yesterday [@ ICHEP]

Direct constraints

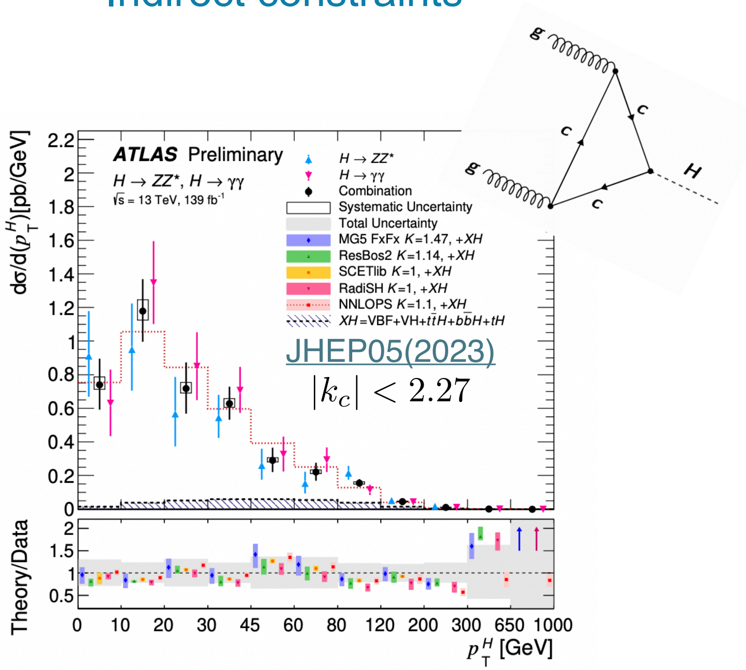


Sensitivity is far from an evidence of Yc
EPJC10052

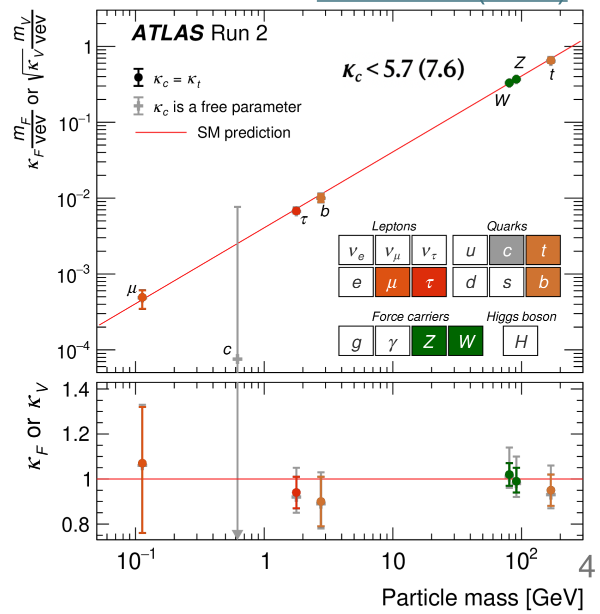


New for ICHEP

Indirect constraints



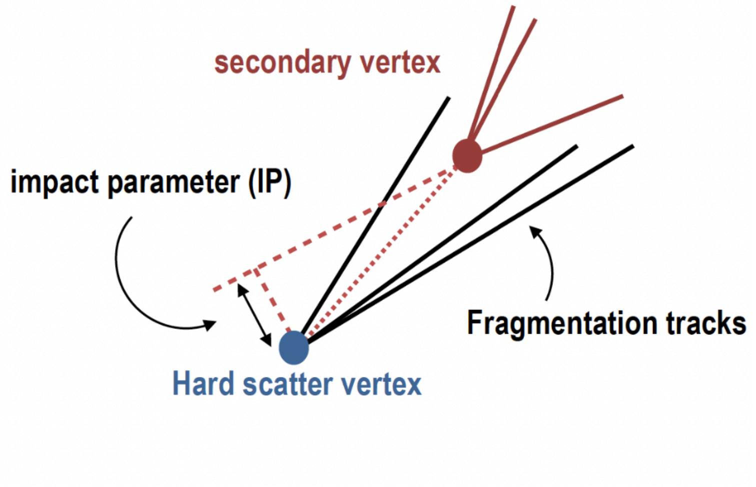
Nature 607(2022)

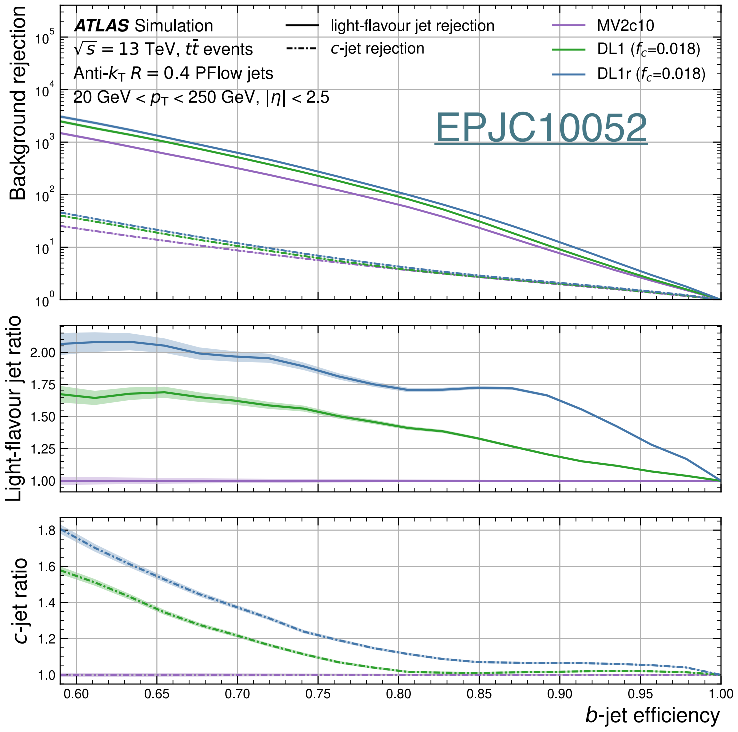


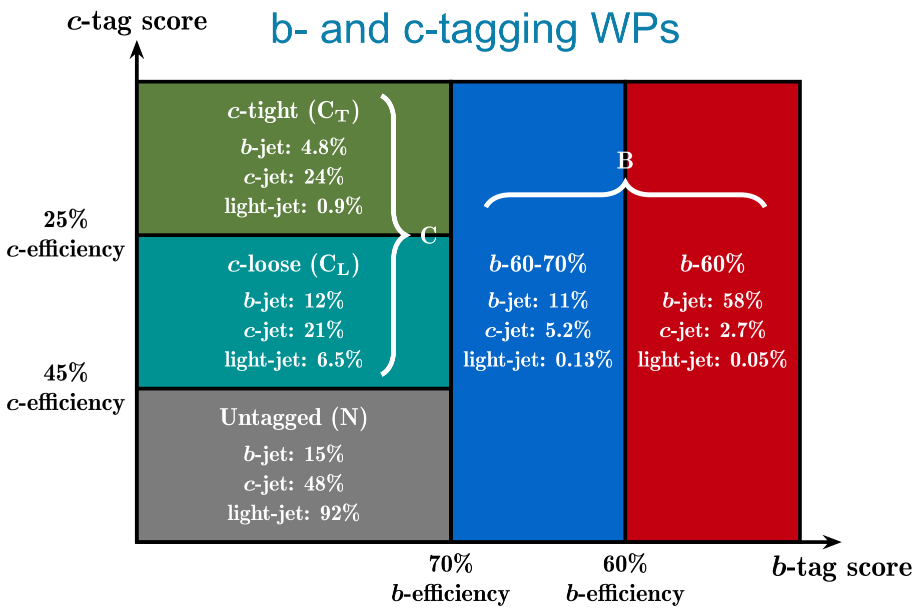
*NB: VH(cc) analysis included

Experimental ingredient: the identification of b- and c-jets

- Most of the results based on the DL1r tagger, a deep neural network that for each jet outputs the probability of being originated by a b-, c- or light-quarks
- b- and c-tagging working point obtained orthogonally
- Dedicated calibrations performed in these working points (see backup). Calibration precision O(10%) for c-jets and O(3%) for b-jets





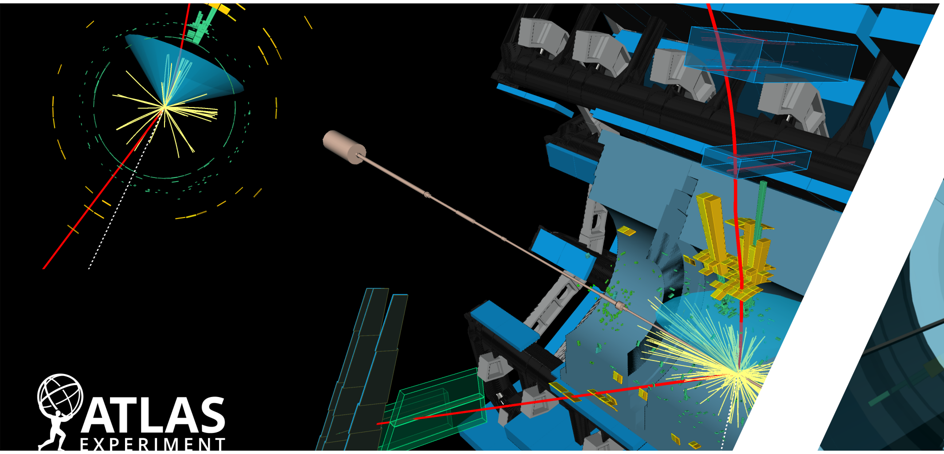


NB: Example, used for the VH analysis

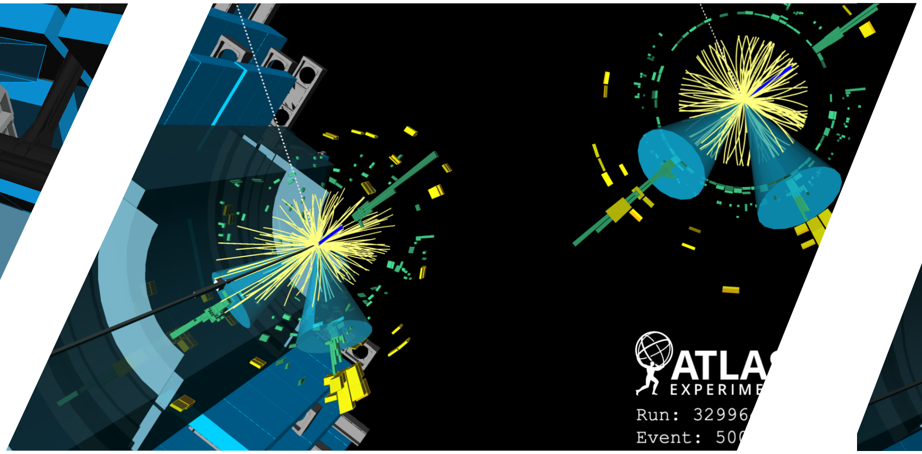
A new result from V(lep)H(bb/cc)

- A new results based on a simultaneous re-analysis of the VH(bb) and VH(cc) analyses
- V=Z/W bosons, split into 0, 1, and 2 muons, electrons or taus
- Analysis also split between resolved (small-R jets, R = 0.4) and boosted (large-R jets, R=1.0), and number of additional jets

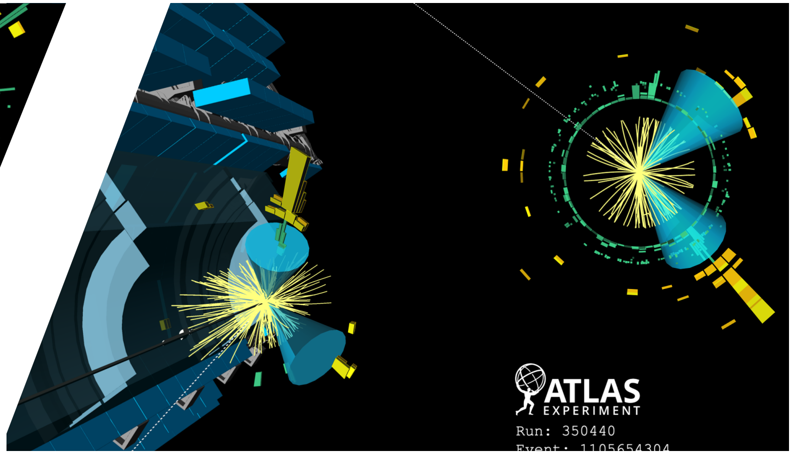
Boosted 1L channel
V transverse momentum > 400 GeV

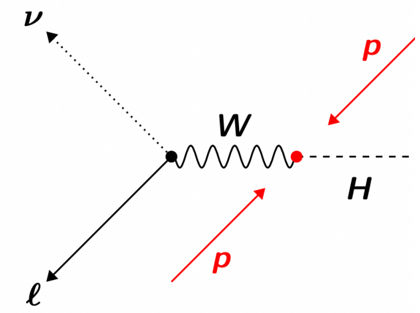


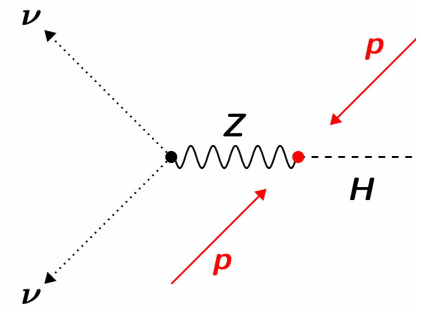
Resolved 1L channel
V transverse momentum < 400 GeV



Resolved 0L channel
V transverse momentum < 400 GeV







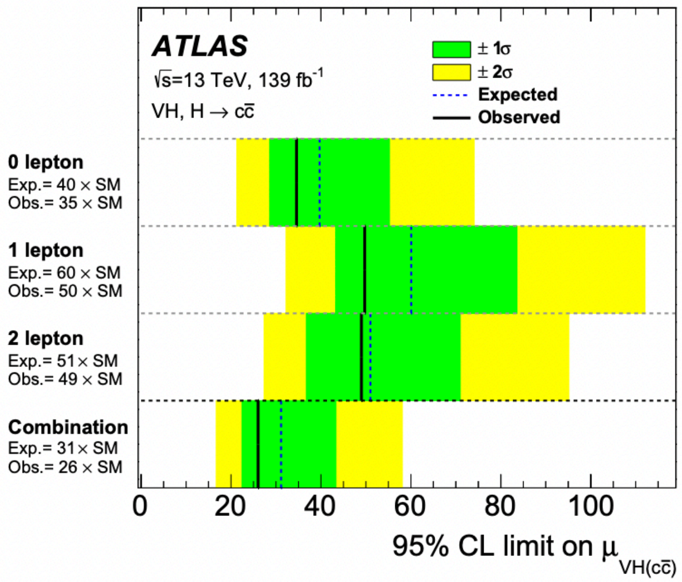
*NB:Illustrative event display

Let's start from the end…

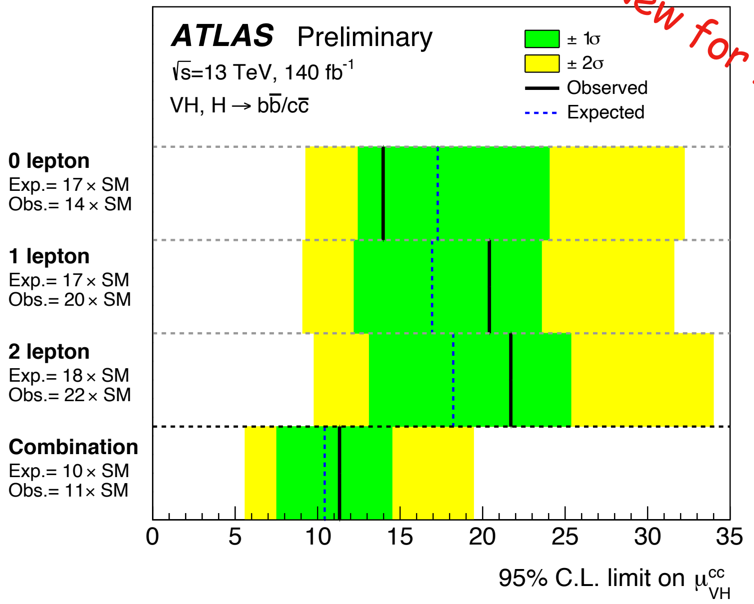
- New Legacy V(led)H(bb/cc) improves and combine previous results: V(lep)H(cc), V(lep)H(bb), boosted V(lep)(Hbb)
- Significant improvements and changes to the analysis in both: VH(bb) and VH(cc) analyses , main ones are related to:

1. Better Flavour tagging (MV2 to DL1r EPJC63,681), and dedicated WPs optimizations
2. Introduced BDT discriminant for VH(cc) and VH(bb) boosted (see backup)
3. New MC samples JHEP08(2022) with much higher stat and dedicated treatment of "truth-tagging": ATLAS 2022-041
4. Increased statistics of alternative generators using CARL, based on: 506.02169
5. Inclusion of additional analysis regions, such as 75-150 pTV in 1L, improved mass resolution

OLD results



More than factor of 2 improvement



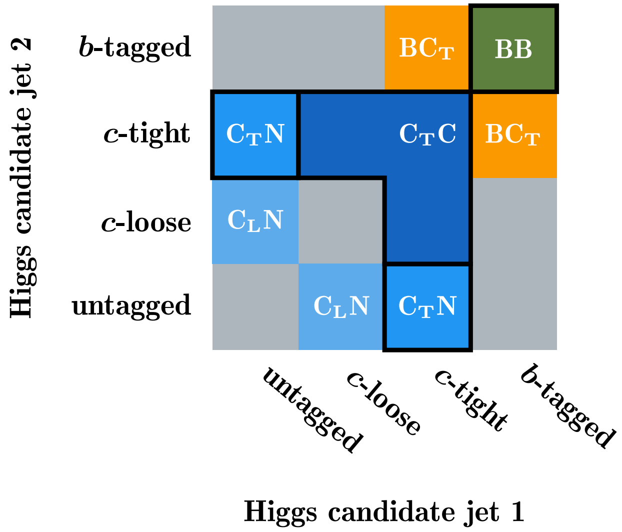
New for ICHEP

VHbb also improved O(20%), and many others exciting results…

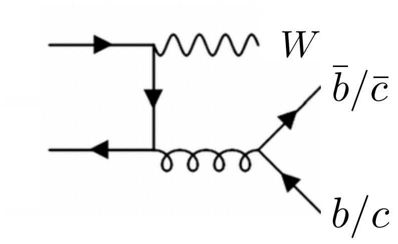
The V(lep)H(bb/cc) analysis in a nutshell

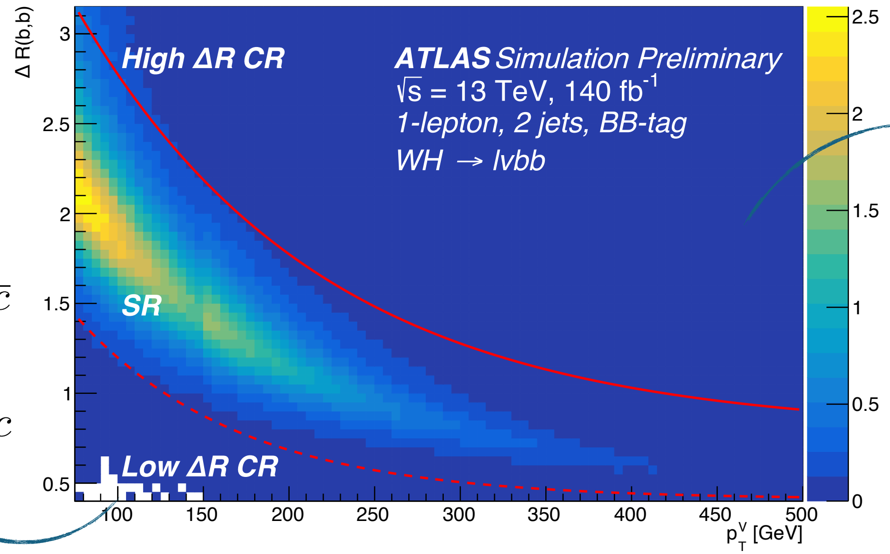
H(bb) SR; H(cc) SRs

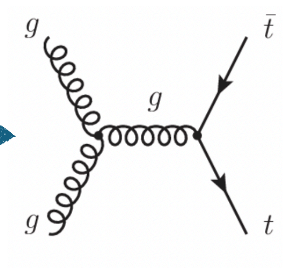
V+jets CR; Top CR



- Orthogonal b- and c-tagging selections applied to form the Higgs candidate and categorise the events into SRs and CRs
- Main backgrounds are Top, Z/W+jets. Need control over Z+heavy flav, Z+light jets etc… Other background are multi-jet, Diboson (also used as a standard candle)
- MC simulations used for the template, norm. factor from data, relative from and shape have dedicated uncertainties (prior derived from MC)
- Complex fit model, (~50) SRs and (~100) CRs defined by tagging and kinematic requirements, ~50 norm. factor to control backgrounds







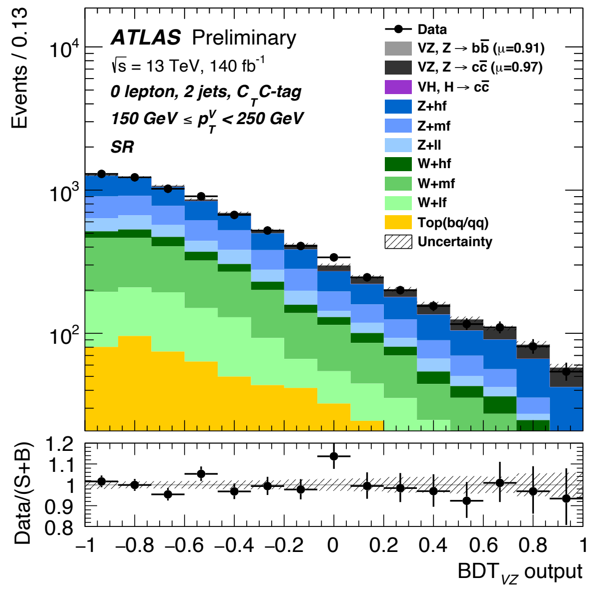
Channel	Region	BB	C$_T$N	C$_T$C$_L$	C$_T$C$_T$	BC$_T$	C$_L$N
0-lepton	High-ΔR CR	Norm. Only				—	
	Top BC$_T$ CR	—				$m_{j_1 j_2}$	—
	V+lf CR	—					Norm. Only
1-lepton	Low-ΔR CR	BDT$_{\text{Low-}\Delta R\text{ CR}}$	—				
	High-ΔR CR	p_T^V		$m_{j_1 j_2}$		—	
	Top BC$_T$ CR	—				$m_{j_1 j_2}$	—
	V+lf CR	—					p_T^V
2-lepton	High-ΔR CR	p_T^V		$m_{j_1 j_2}$		—	
	Top BC$_T$ CR	—	Norm. Only				—
	V+lf CR	—					p_T^V

*NB: discriminant variables used in fit for CRs

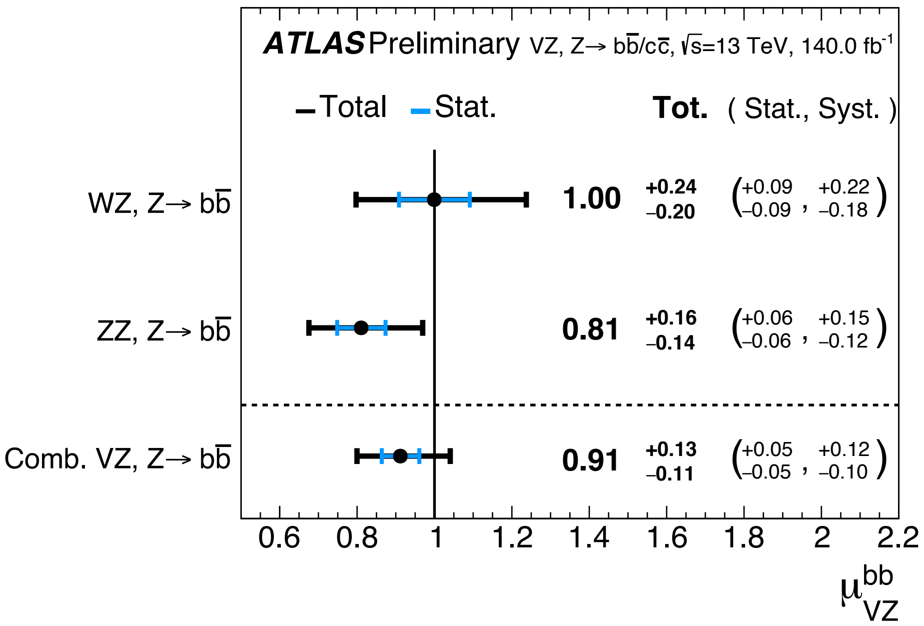
The diboson standard candle

- A BDT trained using VZ as signal, powerful test of the robustness of the analysis
- Similarly to the signal VH, VZ(bb/cc) is simultaneously extracted. Compatible with SM.
- Sensitivities:
  1. WZ(bb): 6.4 (6.5) obs. (exp) σ. First observation ; ZZ(bb) greater than 10
  2. WZ(cc): 3.9 (2.7); ZZ(cc) 3.1 (4.2). First ATLAS measurement of VZ(cc) at 5 std. dev.

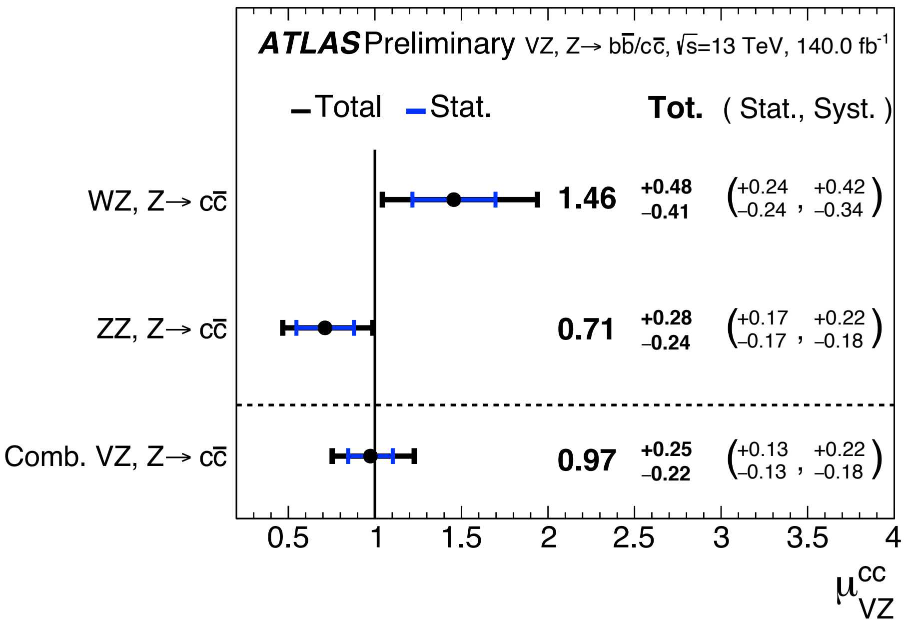
0L, 2-ctag region



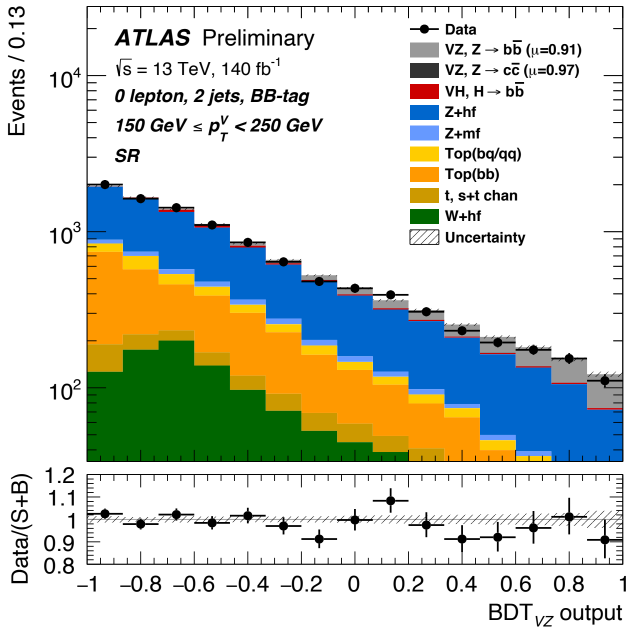
Z -> bb



Z -> cc



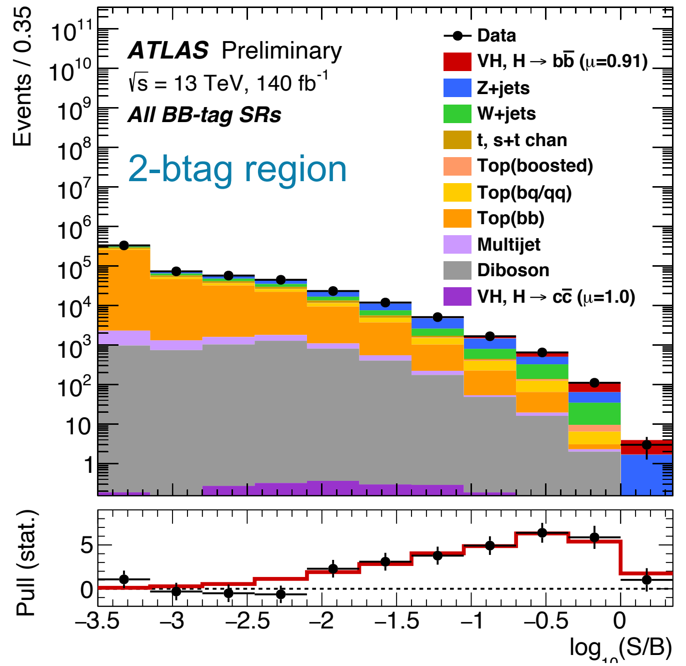
0L, 2-btag region

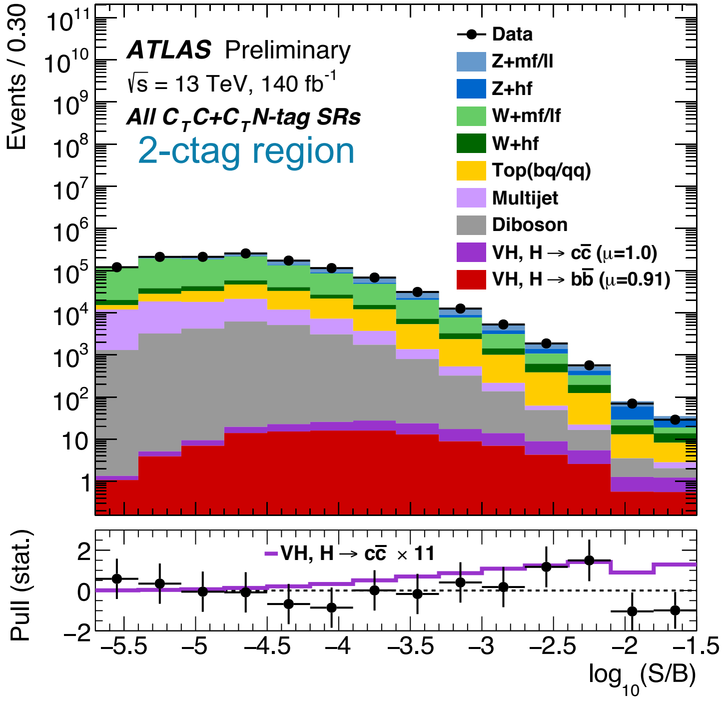


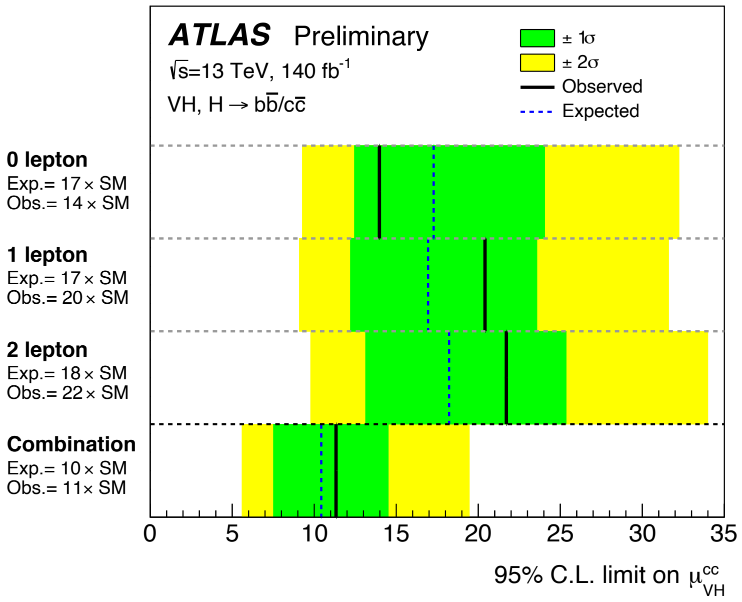
Inclusive results of V(lep)H(bb/cc)

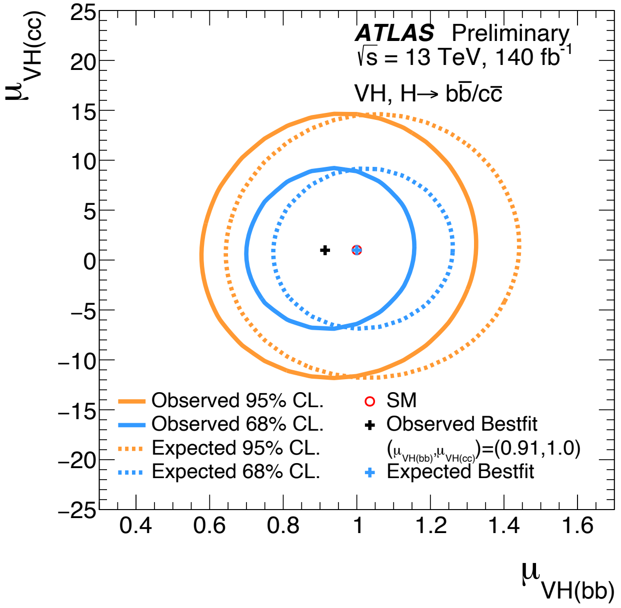
- Simultaneous extraction of VH(bb/cc). Sensitivities:
  1. WH(bb): 5.3 (5.5) obs (exp) ; ZH(bb): 4.9 (5.7) std. dev., VH(bb) around 15% precision
  2. VH(cc) limits at 95% CL is 11.2 (10.4), strongest observed limit to date

$$\mu^{bb}_{VH} = 0.91^{+0.16}_{-0.14} = 0.91 \pm 0.10\,(\text{stat.})^{+0.12}_{-0.11}\,(\text{syst.})$$
$$\mu^{cc}_{VH} = 1.0^{+5.4}_{-5.2} = 1.0^{+4.0}_{-3.9}\,(\text{stat.})^{+3.6}_{-3.5}\,(\text{syst.}).$$



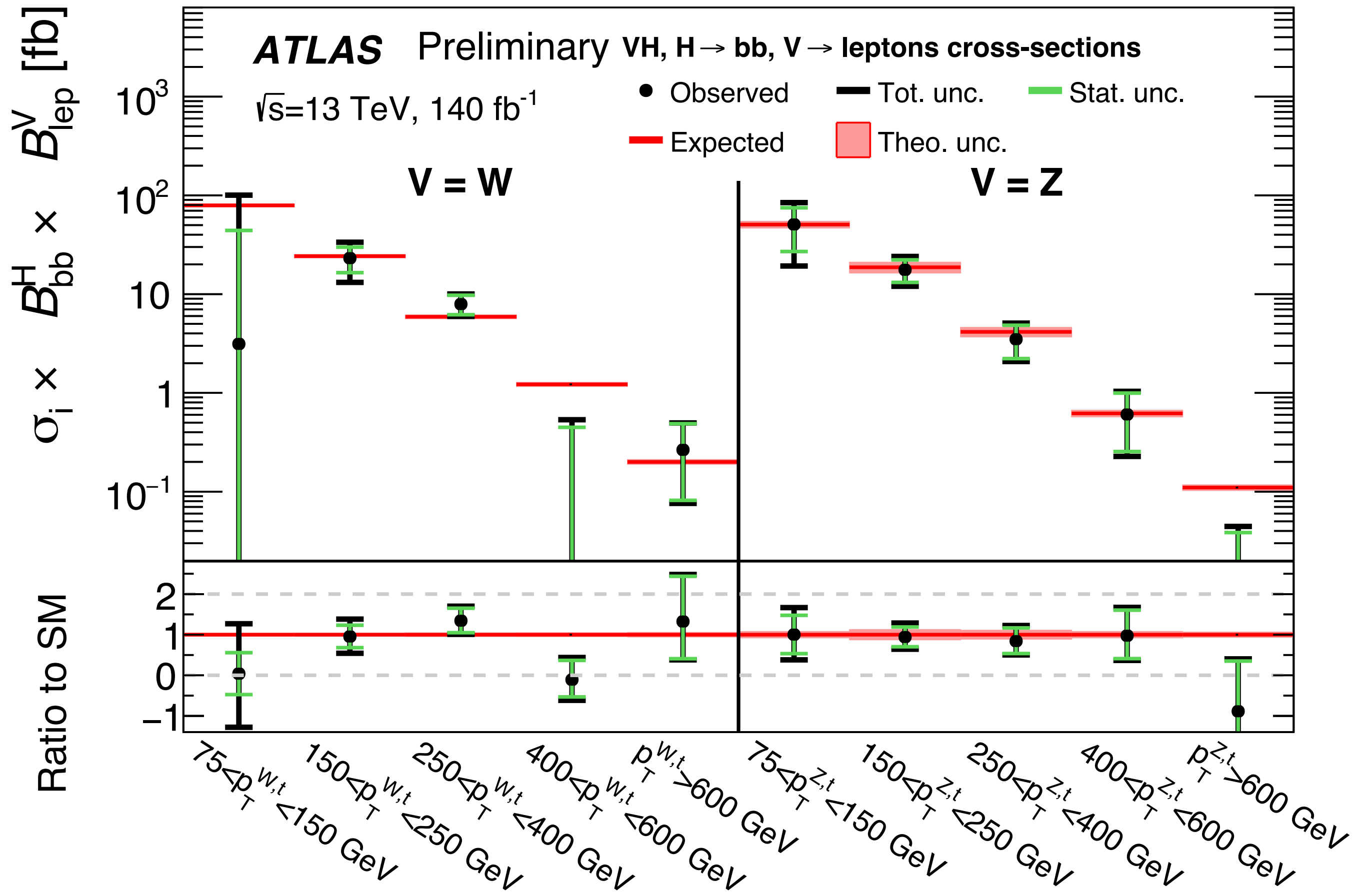






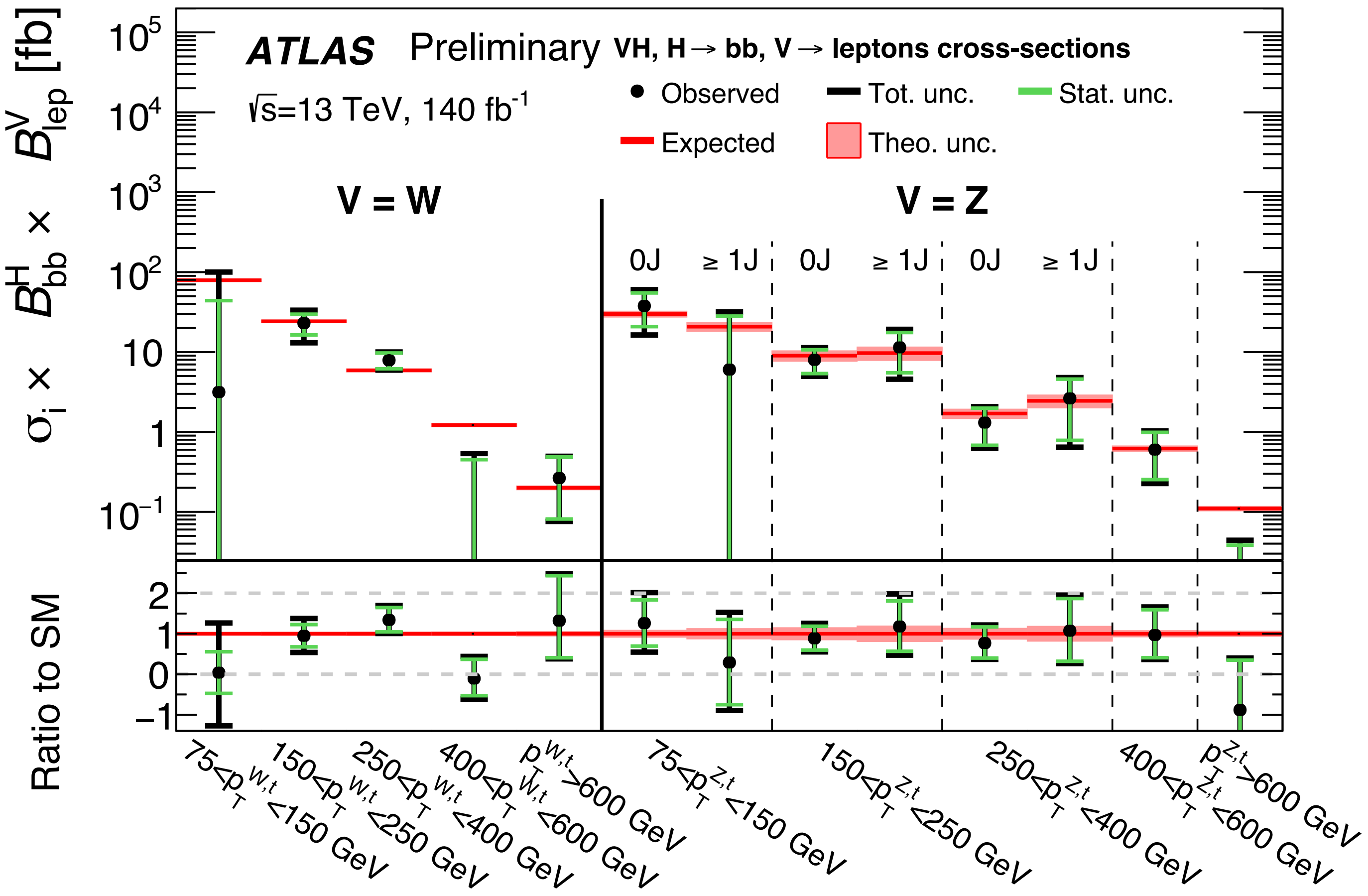
Differential XSec measurement (STXS)

- Added a 75-150 region for WH, new bin at very high transverse momentum (pTV > 600 GeV)
- Improved ZH/WH correlation thanks to dedicated treatment of identified hadronic tau, also improved nJet correlations by harmonising pT cuts



Differential XSec measurement (STXS)

- Added a 75-150 region for WH, added different nJ region for ZH, new bin at very high transverse momentum (pTV > 600 GeV)
- Improved ZH/WH correlation thanks to dedicated treatment of identified hadronic tau, also improved nJet correlations by harmonising pT cuts



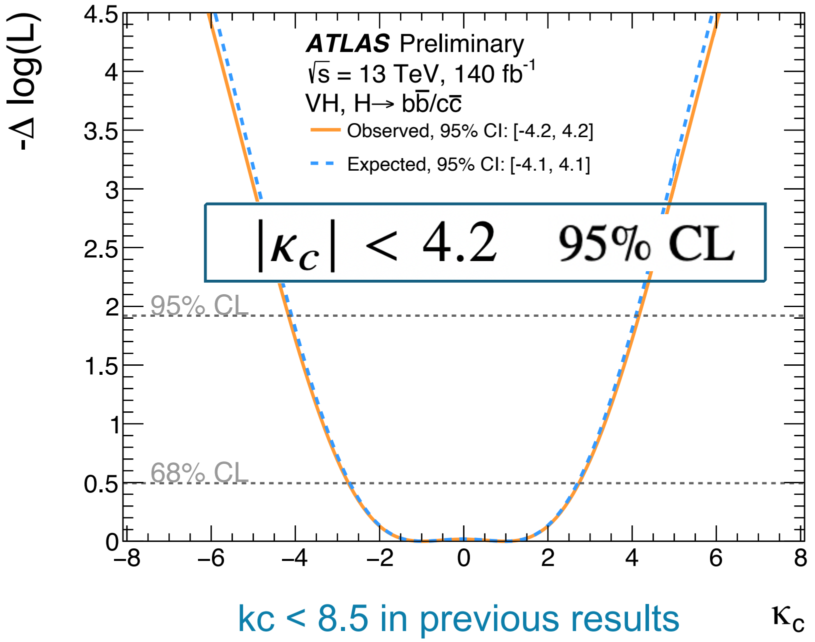
Coupling modifiers, kappa framework

- Results interpreted with coupling modifiers kb and kc (only decay parametrised), others fixed to 1

$$\mu_{VH}^{cc} = \frac{\kappa_c^2}{1 + B_{hbb}^{SM}(\kappa_b^2 - 1) + B_{hcc}^{SM}(\kappa_c^2 - 1)} \qquad \mu_{VH}^{bb} = \frac{\kappa_b^2}{1 + B_{hbb}^{SM}(\kappa_b^2 - 1) + B_{hcc}^{SM}(\kappa_c^2 - 1)}$$

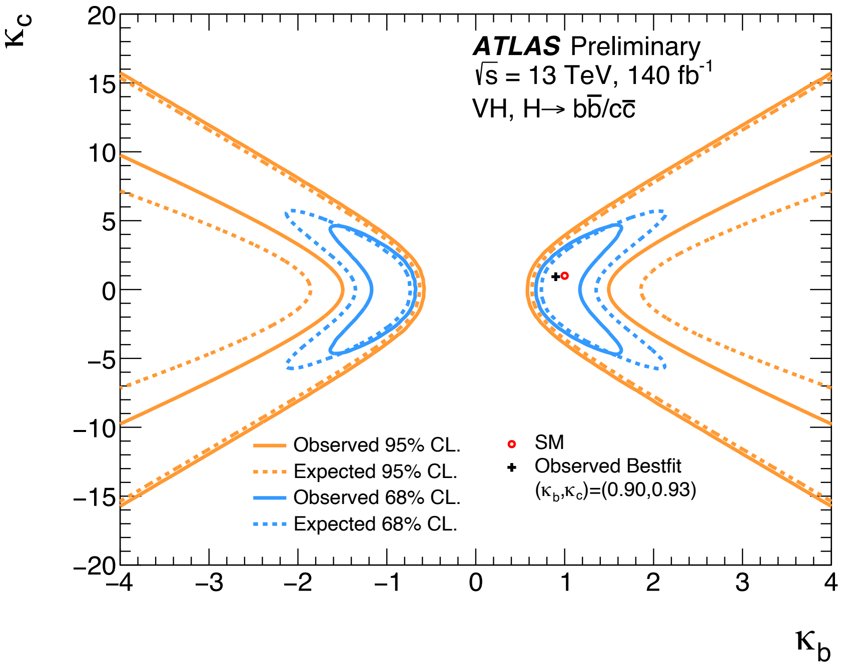
- Previous extrapolation ATL-PHYS-PUB-2021-039 at HL-LHC estimated |kc| < 3 @ 95% CL, we are now with full RUN2 dataset at 4.2!

1D scan fixing kb = 1

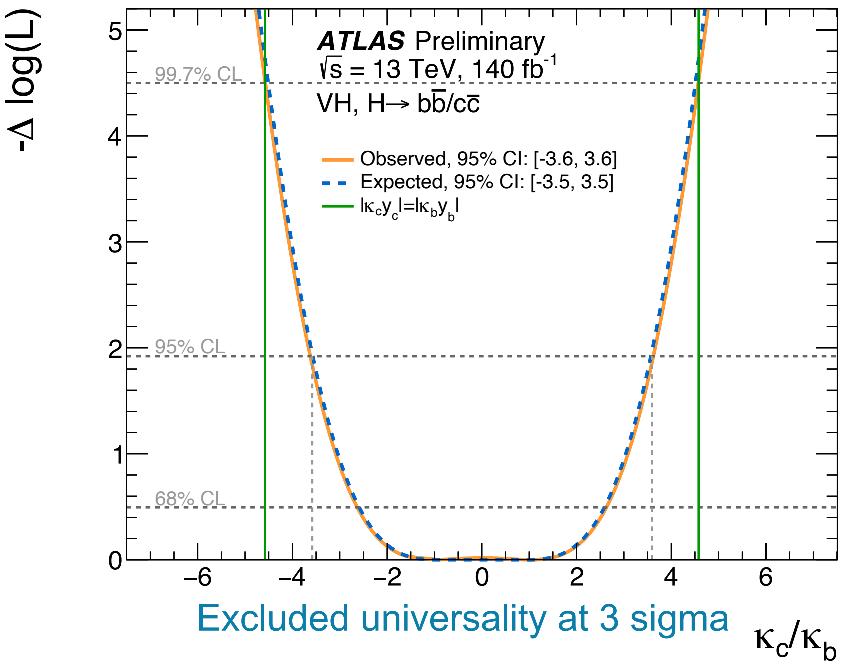


kc < 8.5 in previous results

2D scan, both kb and kc floating



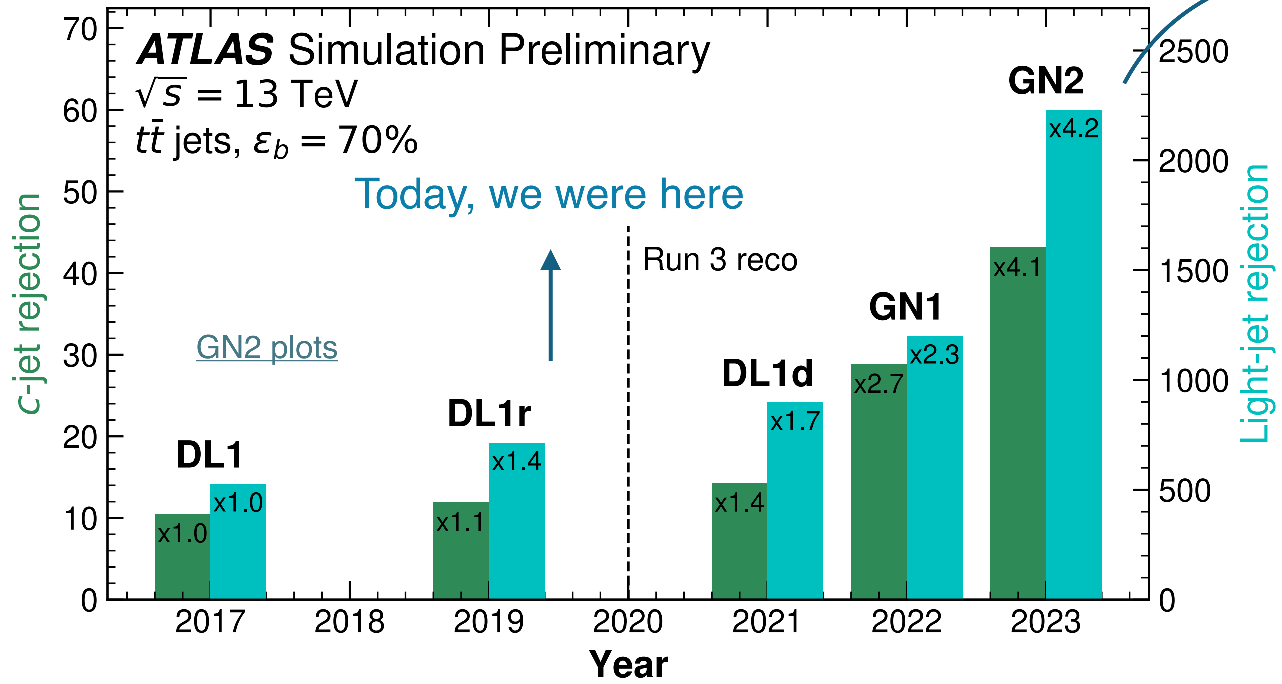
Alternative parametrisation on the ratio, no width dependence



Excluded universality at 3 sigma

Conclusions

- An overview of the analyses sensitive to Y_b and the quest to measure Y_c in ATLAS have been summarised
- Main novel results is related to the V(lep)H(bb/cc) legacy analysis, which shows significant improvement:
  - First observation of VZ(cc) and WZ(bb), used as a cross-check for the analysis
  - Observation of WH(bb), improved STXS measurements in both granularity and precision, best results to date
  - Best observed limit up to date on VH(cc), significantly improved constraint on the direct charm-yukawa
  - Universality structure of b/c-coupling excluded at 3 σ
- Will we be able to find evidence of the charm-yukawa during the LHC life-time?



Tomorrow, we will be here!

FTAG talk @ ICHEP2024

Big thank you to the VH(bb/cc team)!

Backup

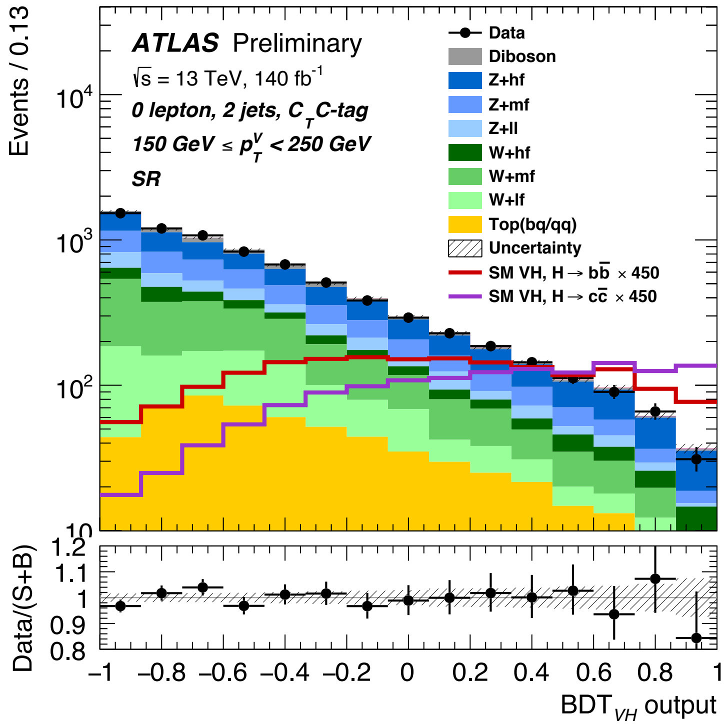
Systematic uncertainties

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		0.151	0.200	0.220	5.29
Statistical		0.097	0.139	0.151	3.94
Systematic		0.116	0.160	0.160	3.53
Statistical uncertainties					
Data statistical		0.089	0.129	0.137	3.70
$t\bar{t}$ $e\mu$ control region		0.009	0.002	0.020	0.06
Background floating normalisations		0.034	0.053	0.040	1.23
Other VH floating normalisation		0.007	0.013	0.007	0.24
Simulation samples size		0.023	0.034	0.030	1.61
Experimental uncertainties					
Jets		0.028	0.039	0.025	1.00
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.009	0.005	0.018	0.24
Leptons		0.004	0.003	0.008	0.23
b-tagging	b-jets	0.020	0.016	0.023	0.30
b-tagging	c-jets	0.013	0.020	0.010	0.73
b-tagging	light-flavour jets	0.006	0.010	0.004	0.67
Pile-up		0.009	0.017	0.003	0.24
Luminosity		0.006	0.007	0.006	0.08
Theoretical and modelling uncertainties					
Signal		0.073	0.066	0.112	0.56
Z + jets		0.039	0.018	0.079	1.76
W + jets		0.055	0.087	0.027	1.41
$t\bar{t}$ and Wt		0.018	0.033	0.018	1.03
Single top quark (s-, t-ch.)		0.010	0.019	0.003	0.15
Diboson		0.032	0.040	0.048	0.51
Multi-jet		0.006	0.011	0.005	0.57

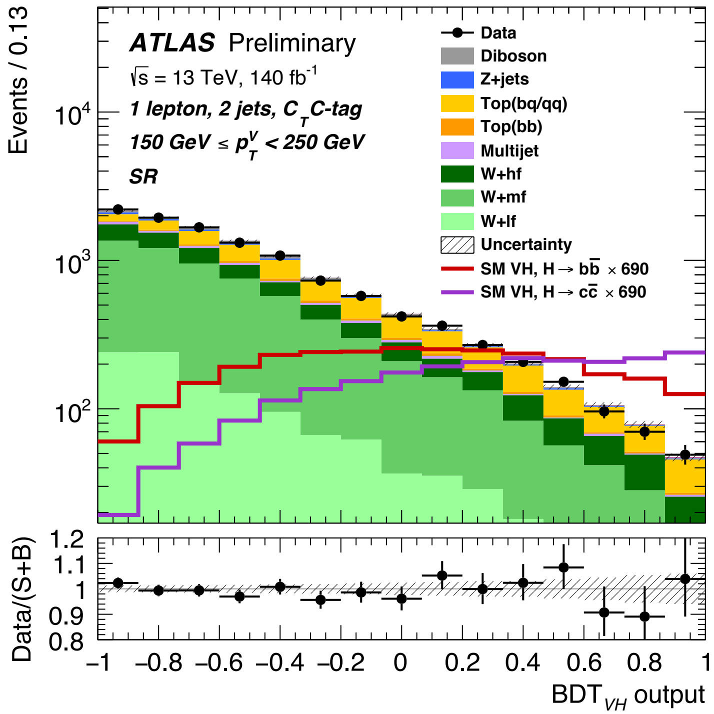
Post-fit plots from the VH(bb/cc) fit

- Post-fit plots of the 2-ctag SR with 150 <pTV< 250 GeV

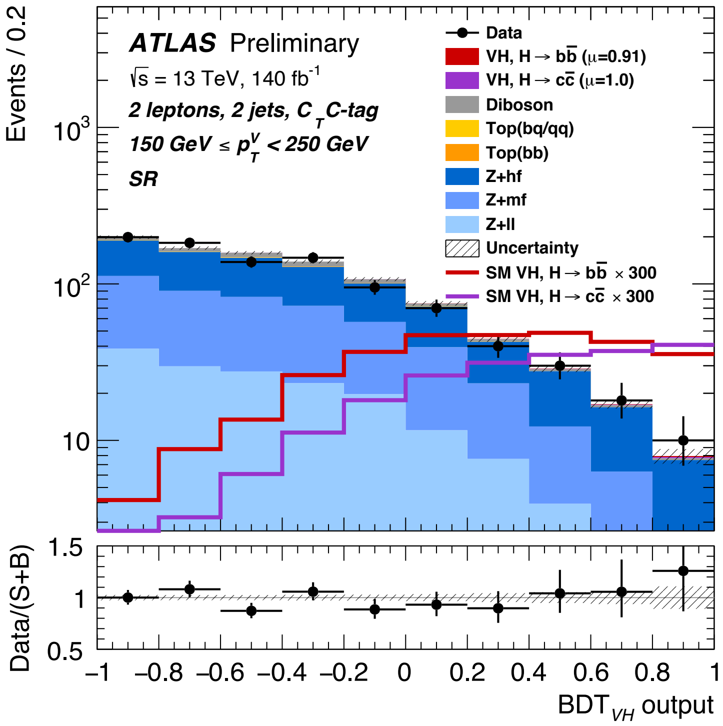
0 lepton



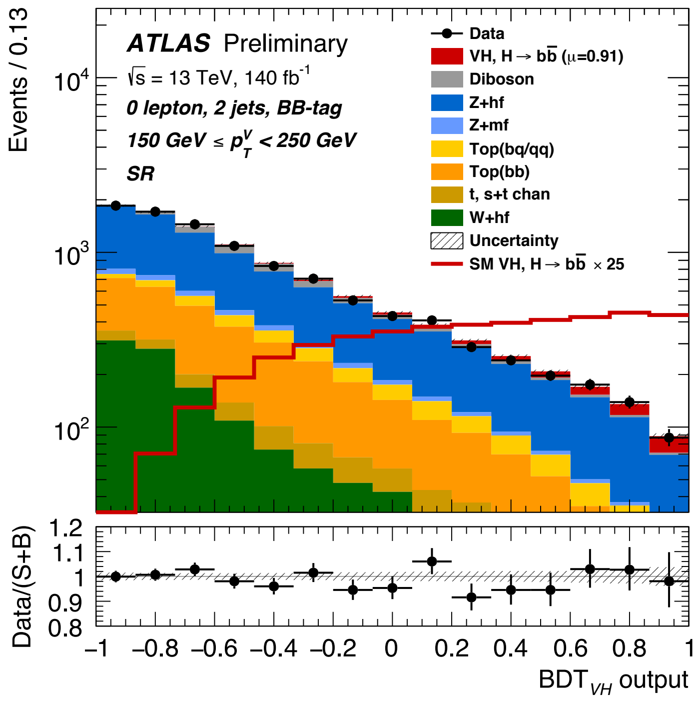
1 lepton

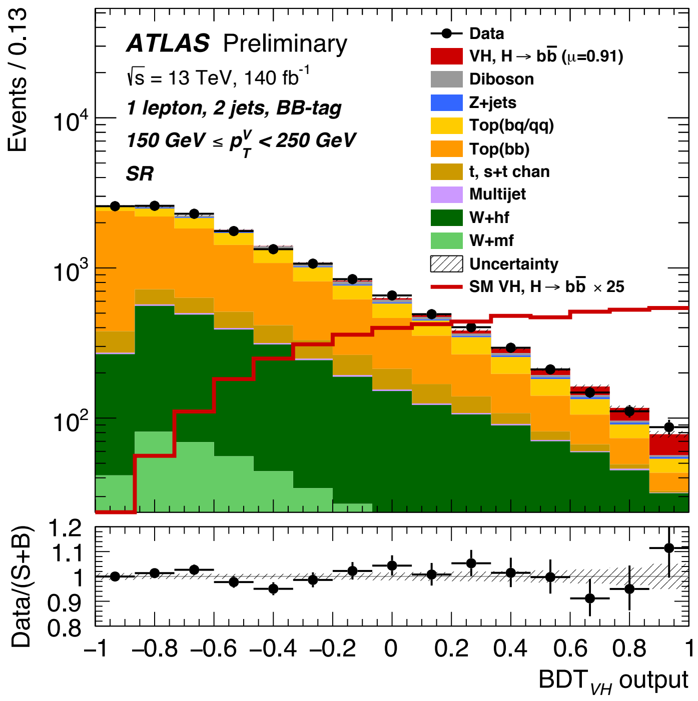


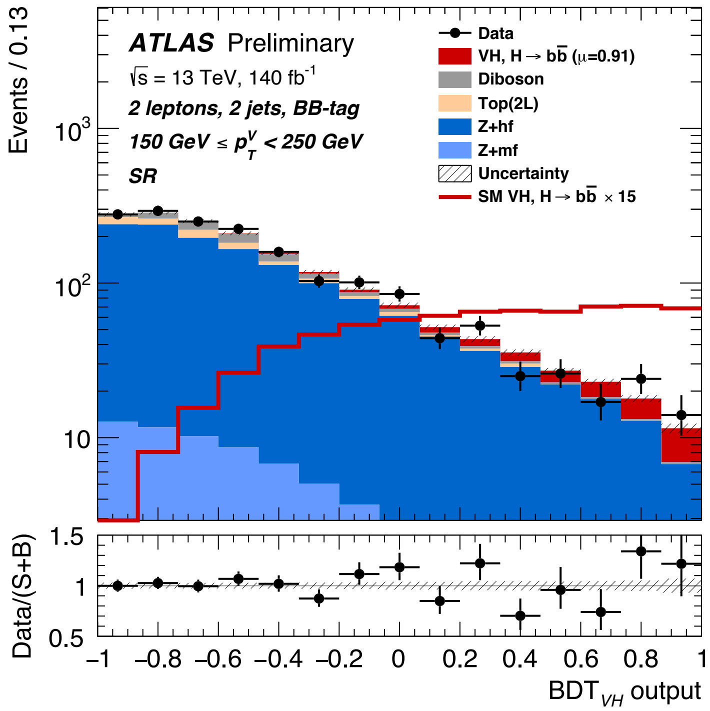
2 leptons



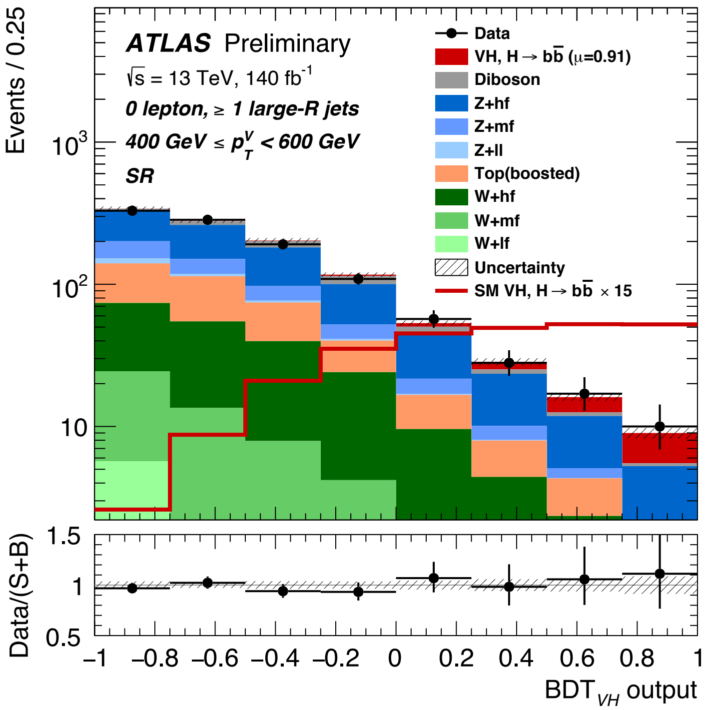
Post-fit VHbb

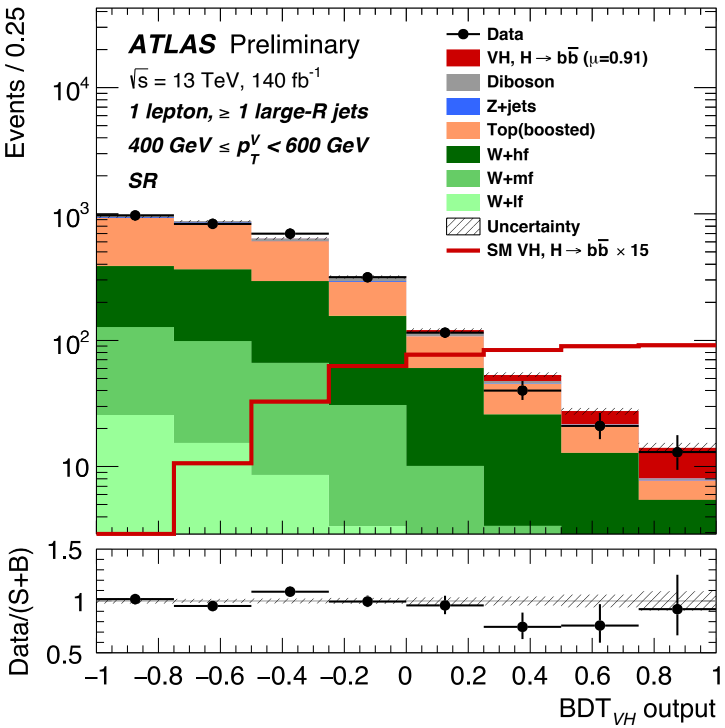


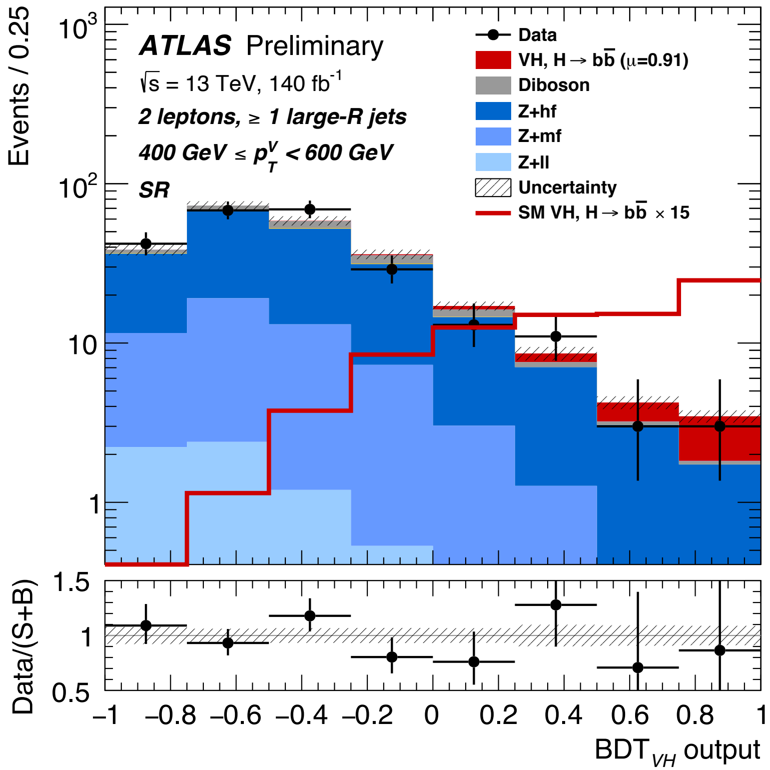




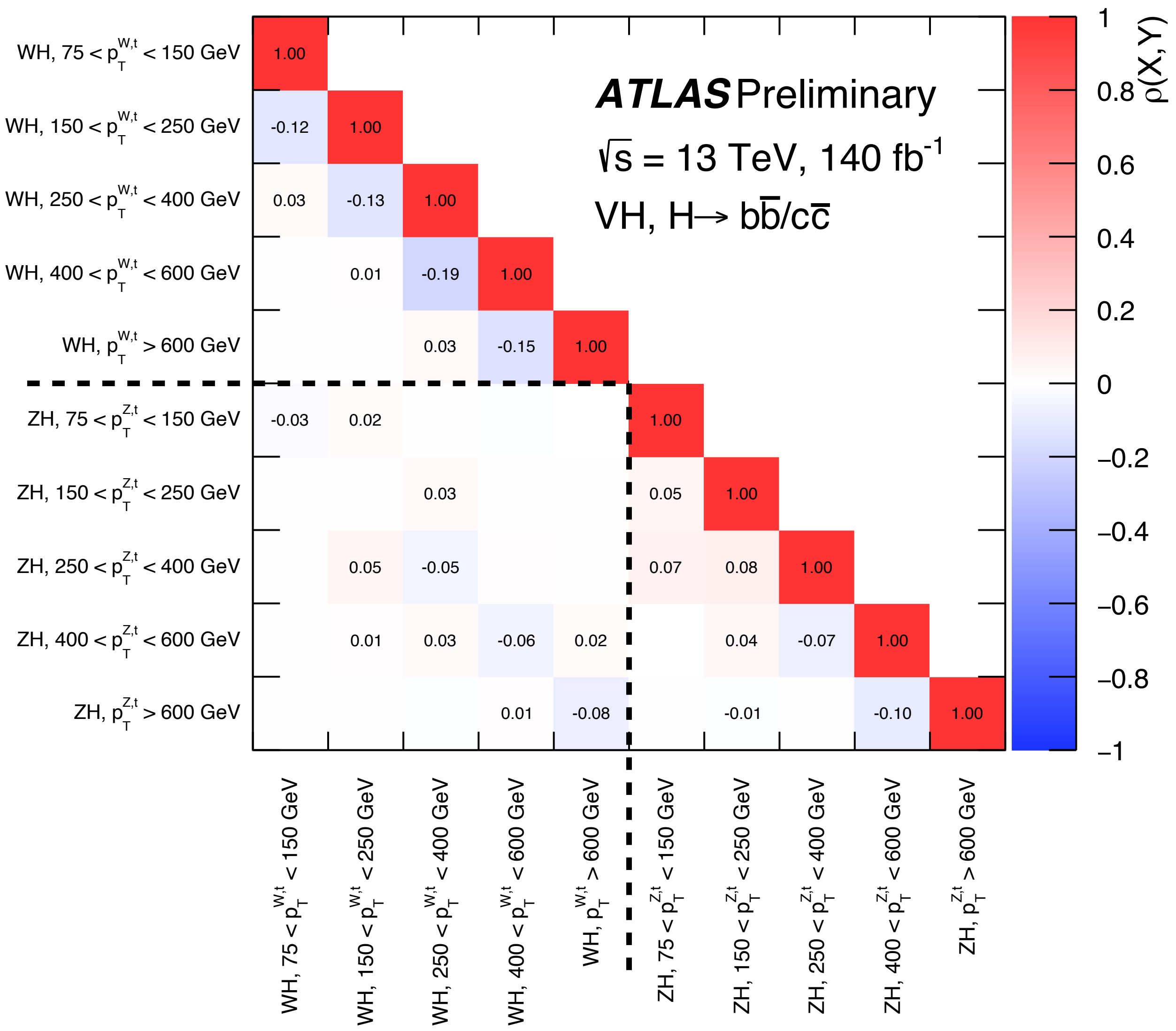
Post-fit VHbb boosted



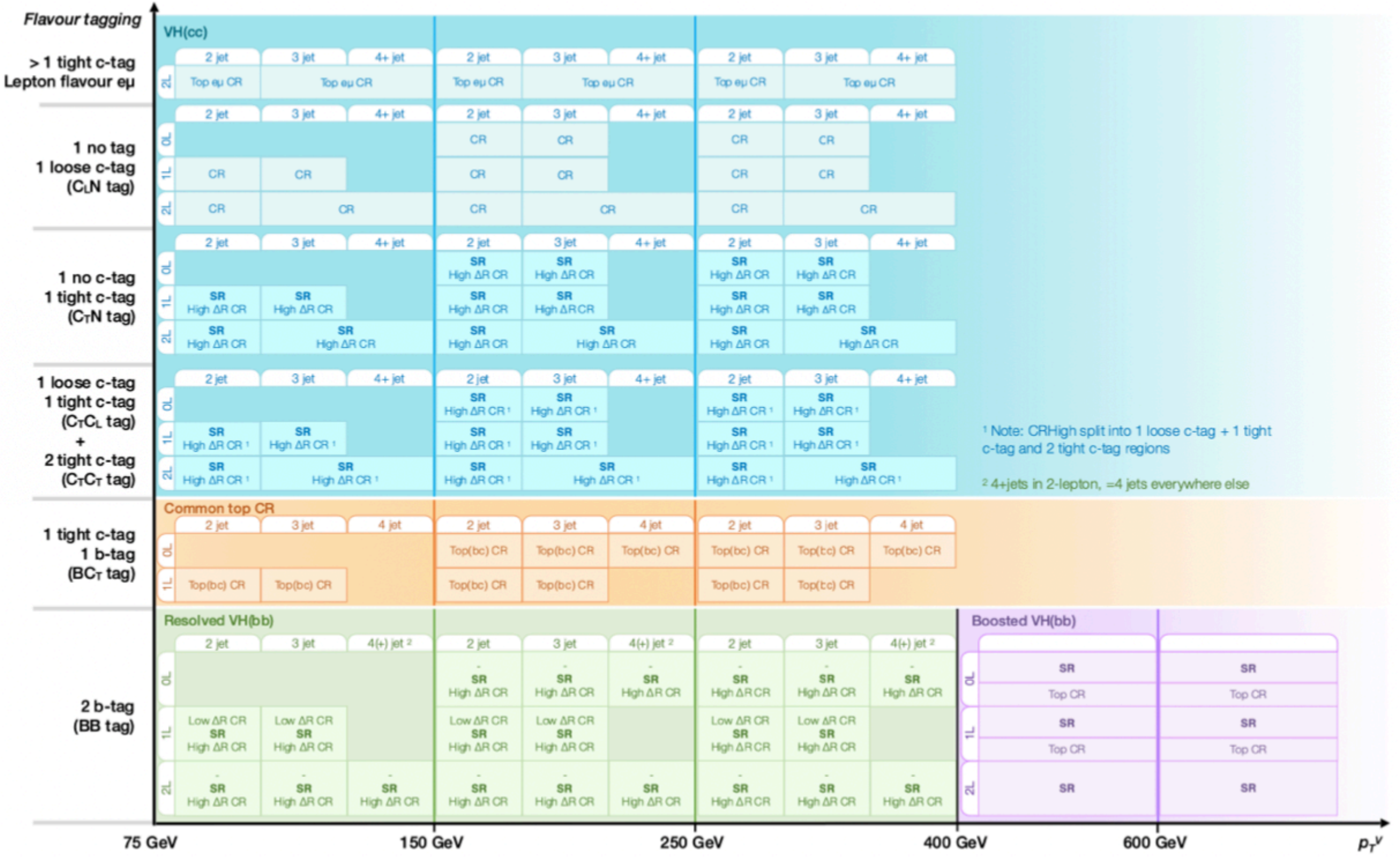




STXS correlations



A more detailed look at the fit region



A complex simultaneous fit over b- and c-tagging bins, ptV regions, and several CRs

NF factors

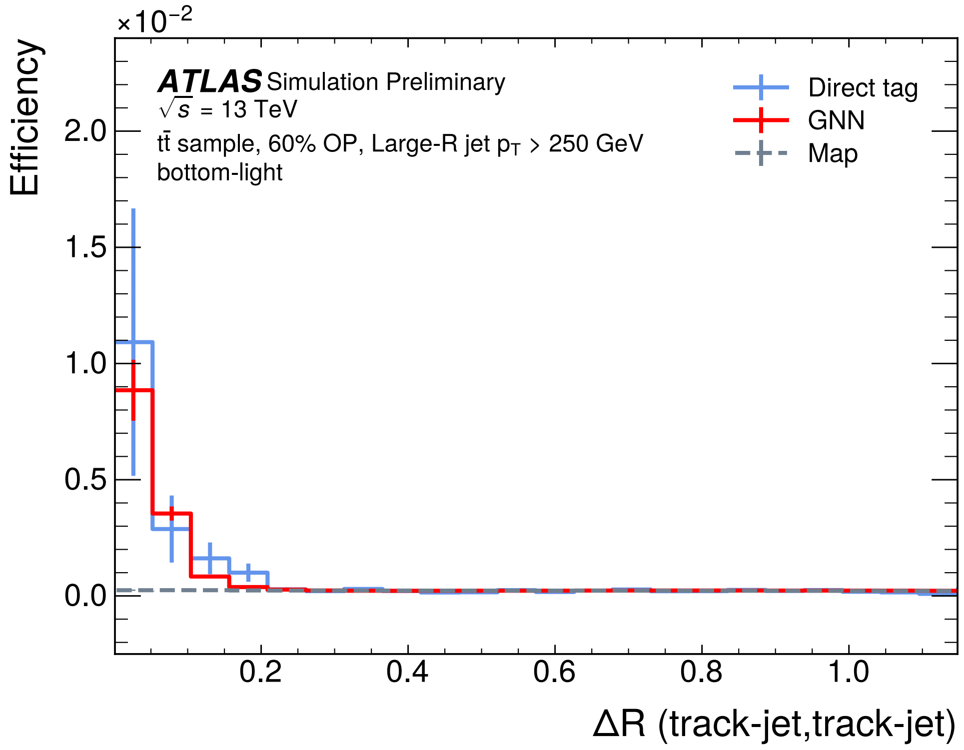
p_T^V region	num. jet	Top(bb)	Top(bq,qq)	Top 2L
[75,150] GeV	2	1.02 ± 0.04	0.98 ± 0.05	1.05 ± 0.05
	3	0.97 ± 0.03	0.98 ± 0.03	0.98 ± 0.05
[150,250] GeV	2	0.89 ± 0.05	0.83 ± 0.04	1.07 ± 0.16
	3	0.91 ± 0.03	0.86 ± 0.03	0.95 ± 0.14
	4	0.97 ± 0.02	0.95 ± 0.03	
[250,400] GeV	2	0.78 ± 0.08	0.82 ± 0.05	1.10 ± 0.50
	3	0.83 ± 0.04	0.80 ± 0.03	
	4	0.93 ± 0.05	0.86 ± 0.04	
[400,600[GeV	-	0.83 ± 0.05		-
>600 GeV	-	0.69 ± 0.07		-

p_T^V region	num. jet	$W+hf$	$W+mf$	$W+lf$
[75,150] GeV	2	1.09 ± 0.06	1.20 ± 0.03	1.03 ± 0.04
	≥3	1.30 ± 0.07	1.16 ± 0.04	1.07 ± 0.05
[150,250] GeV	2	1.00 ± 0.05	1.31 ± 0.03	1.08 ± 0.03
	≥3	1.28 ± 0.07	1.31 ± 0.04	1.07 ± 0.04
[250,400] GeV	2	0.97 ± 0.08	1.35 ± 0.07	1.05 ± 0.03
	≥3	1.46 ± 0.12	1.32 ± 0.07	1.10 ± 0.04
[400,600] GeV	-	1.49 ± 0.25		–
>600 GeV	-	2.03 ± 0.25		–

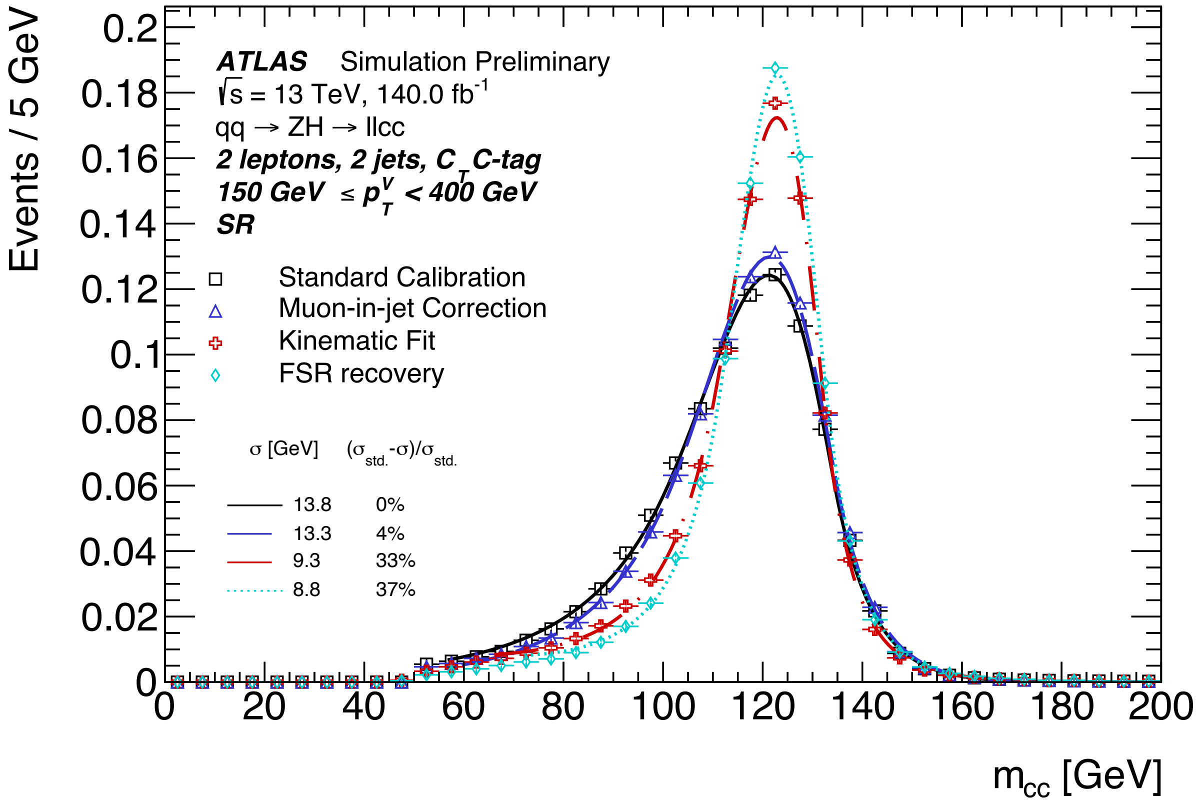
p_T^V region	num. jet	$Z+hf$	$Z+mf$	$Z+lf$
[75,150] GeV	2	1.20 ± 0.04	1.04 ± 0.04	1.12 ± 0.03
	≥3	1.49 ± 0.06	1.11 ± 0.05	1.12 ± 0.05
	3/≥3	0.77 ± 0.03	–	–
[150,250] GeV	2	1.30 ± 0.04	1.08 ± 0.04	1.17 ± 0.02
	≥3	1.59 ± 0.07	1.14± 0.05	1.17 ± 0.04
	3/≥3	0.80 ± 0.04	–	–
[250,400] GeV	2	1.40 ± 0.07	1.31 ± 0.08	1.16 ± 0.03
	≥3	1.78 ± 0.09	1.32 ± 0.07	1.20 ± 0.04
	3/≥3	0.74 ± 0.04	–	–
>400 GeV	-	1.63 ± 0.13		–

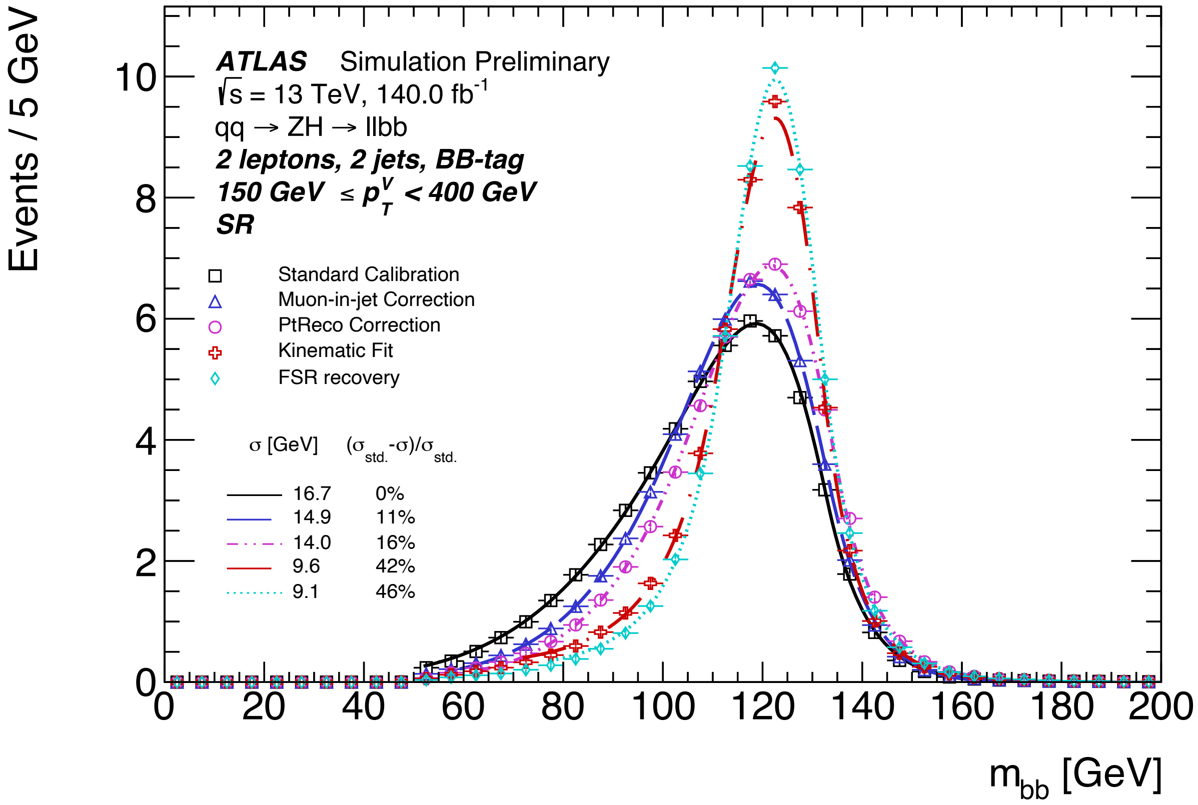
Truth tagging

truth tag note



Mass corrections





Selections of the H+c analysis

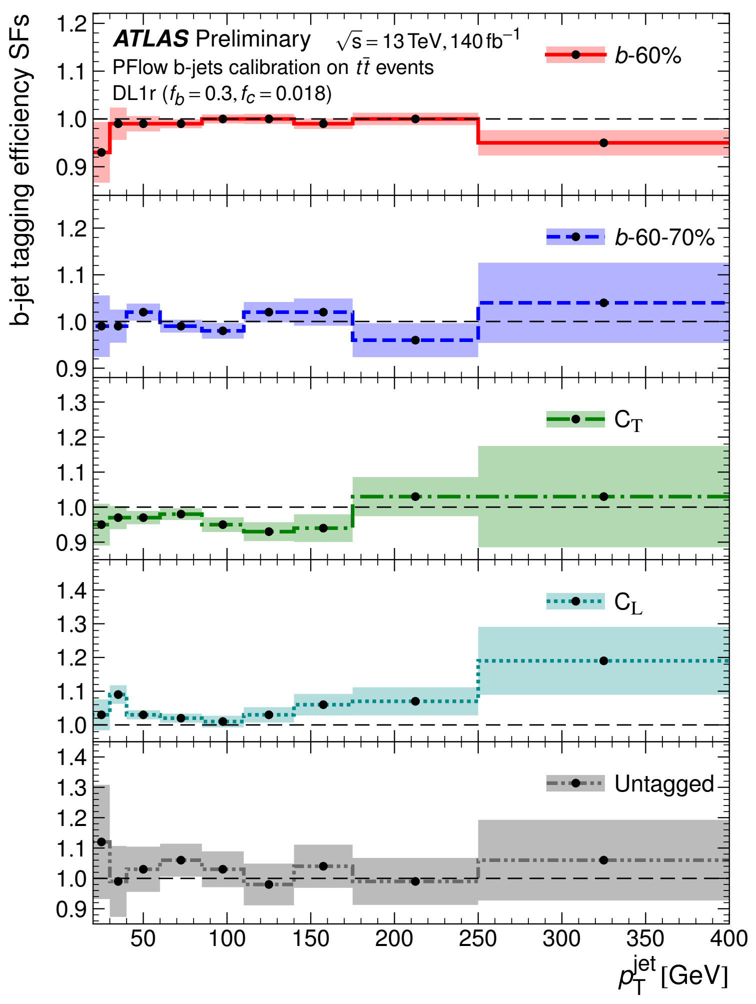
Table 4: Summary of selection and categorisation requirements.

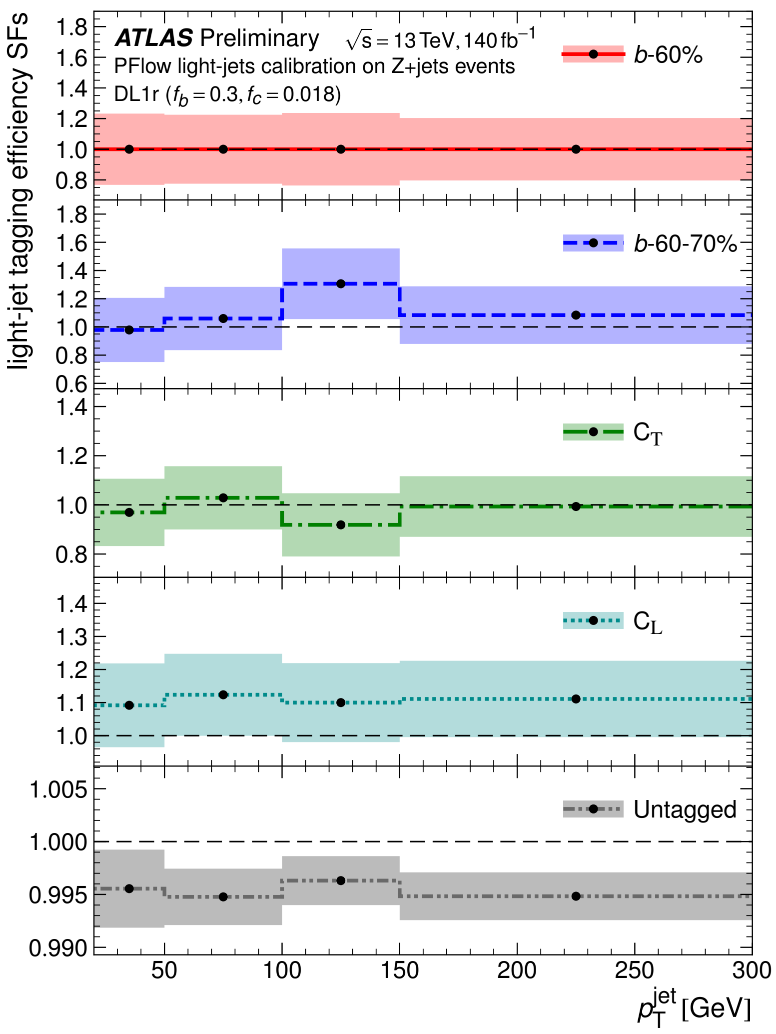
Selection requirements	
Trigger	Di-photons trigger with isolation
Photons	$\geq$ 2 isolated, *tight* identification, p_T >25 GeV, $\lvert\eta\rvert$<2.37, excluding 1.37< $\lvert\eta\rvert$ <152
Relative p_T	$E_T^{\gamma}/m_{\gamma\gamma}$ >0.35 (0.25)
Mass cut	105 GeV < $m_{\gamma\gamma}$ < 160 GeV
Jets	$\leq$ 2, p_T > 25 GeV, $\lvert\eta\rvert$ <2.5
Jets & Photons	$\Delta R(j, \gamma_{1,2}) > 1$
c-tagging	2 categories: $N_{c-\text{tag}}$ =0 or $N_{c-\text{tag}}$ $\geq$1

Samples of the VH analysis

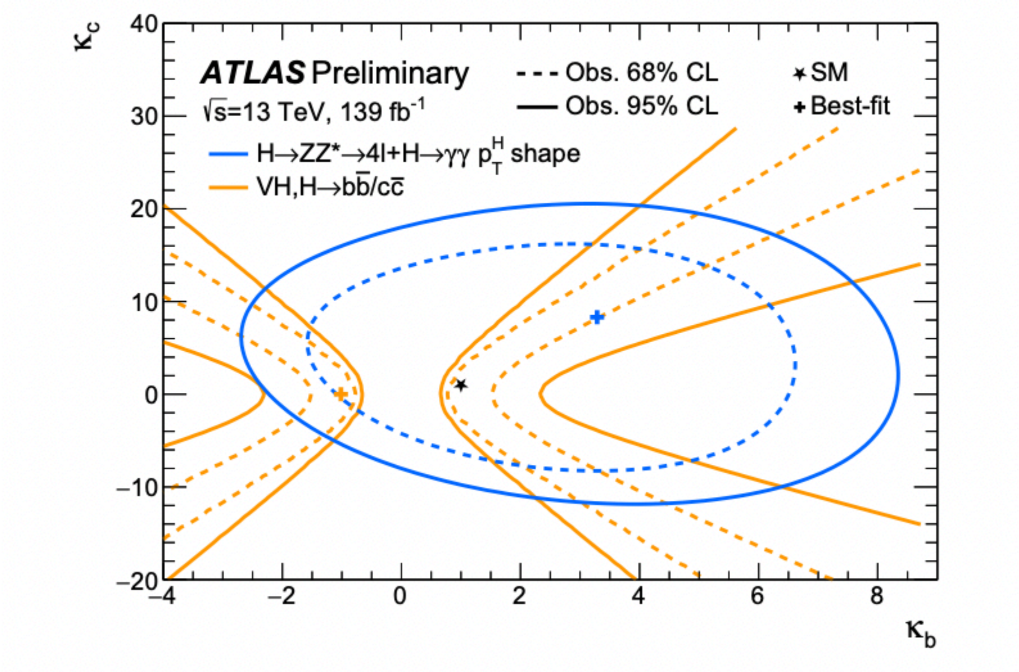
Process	ME generator	ME PDF	PS and Hadronisation	UE tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to VH$	Powheg Box v2 [54] + GoSam [55]+ MiNLO [66, 67]	NNPDF3.0NLO $^{(\star)}$ [56]	Pythia 8.245 [57]	AZNLO [58]	NNLO(QCD)$^{(\dagger)}$+ NLO(EW) [59–65]
$gg \to ZH$	Powheg Box v2	NNPDF3.0NLO $^{(\star)}$	Pythia 8.245	AZNLO	NLO+ NLL [68–72]
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	Powheg Box v2 [73]	NNPDF3.0NLO	Pythia 8.230	A14 [74]	NNLO+NNLL [75]
s-chan. single top	Powheg Box v2 [76]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [77]
t-chan. single top	Powheg Box v2 [76]	NNPDF3.0NLO	Pythia 8.230	A14	NNLO [78]
Wt	Powheg Box v2 [79]	NNPDF3.0NLO	Pythia 8.230	A14	Approx. NNLO+NNLL [80]
Vector boson + jets					
V+jets	Sherpa 2.2.11 [82–84]	NNPDF3.0NNLO	Sherpa 2.2.11 [85, 86]	Default	NNLO [81]
Diboson					
$qq \to VV$	Sherpa 2.2.11	NNPDF3.0NNLO	Sherpa 2.2.11	Default	NLO$^{(\ddagger)}$
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO$^{(\ddagger)}$

Scale-factors

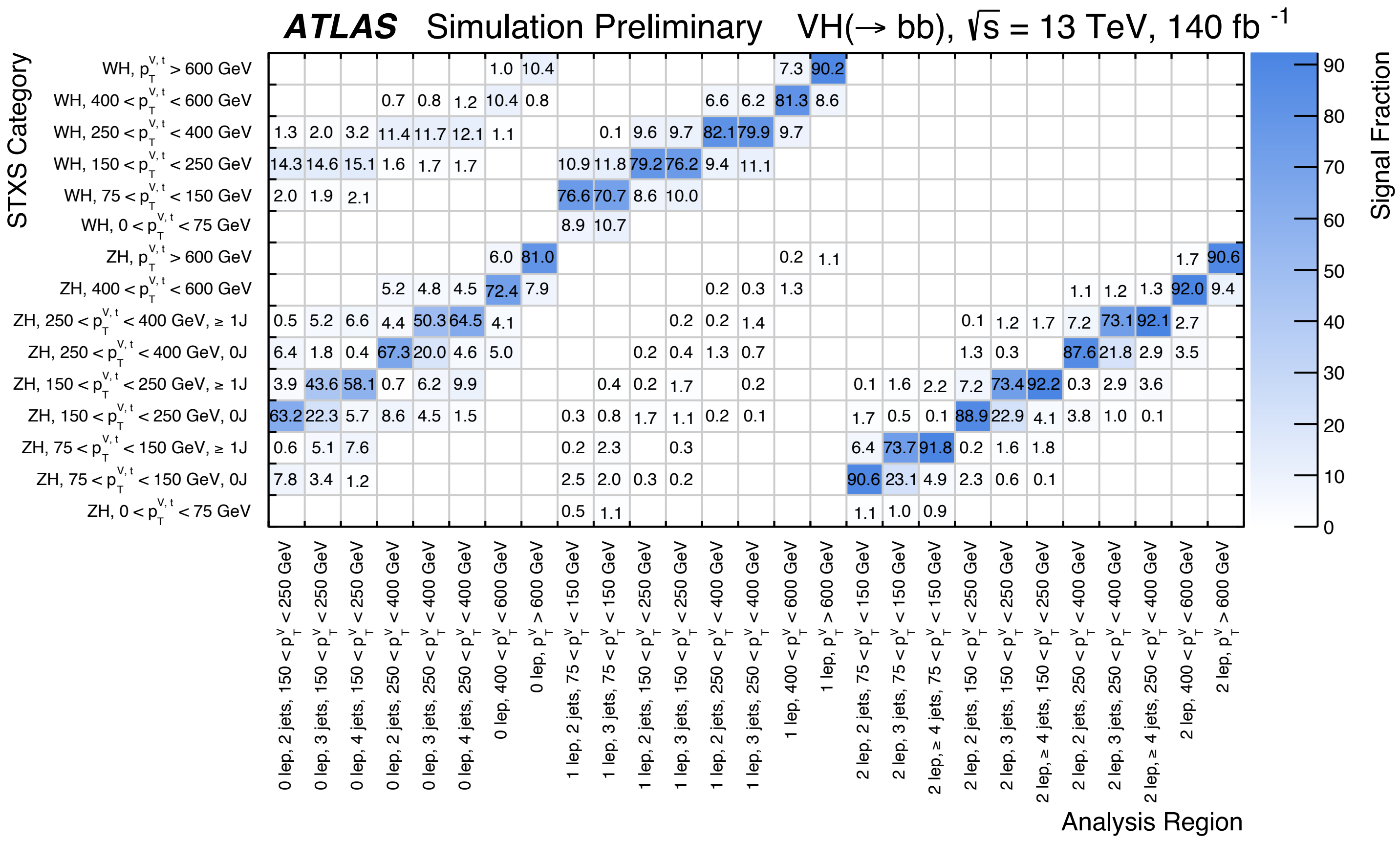




Previous overlay plot on kb-kc



Migration matrix



BDT inputs

Table 2: Variables used for the mutivariate discriminante in each of the channels. The ✓ symbol indicates the inclusion of a variable. The $\text{BDT}_{\text{Low-}\Delta R\ \text{CR}}$ uses the same variables as the 1-lepton resolved Hbb category as described in the text.

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

Background composition