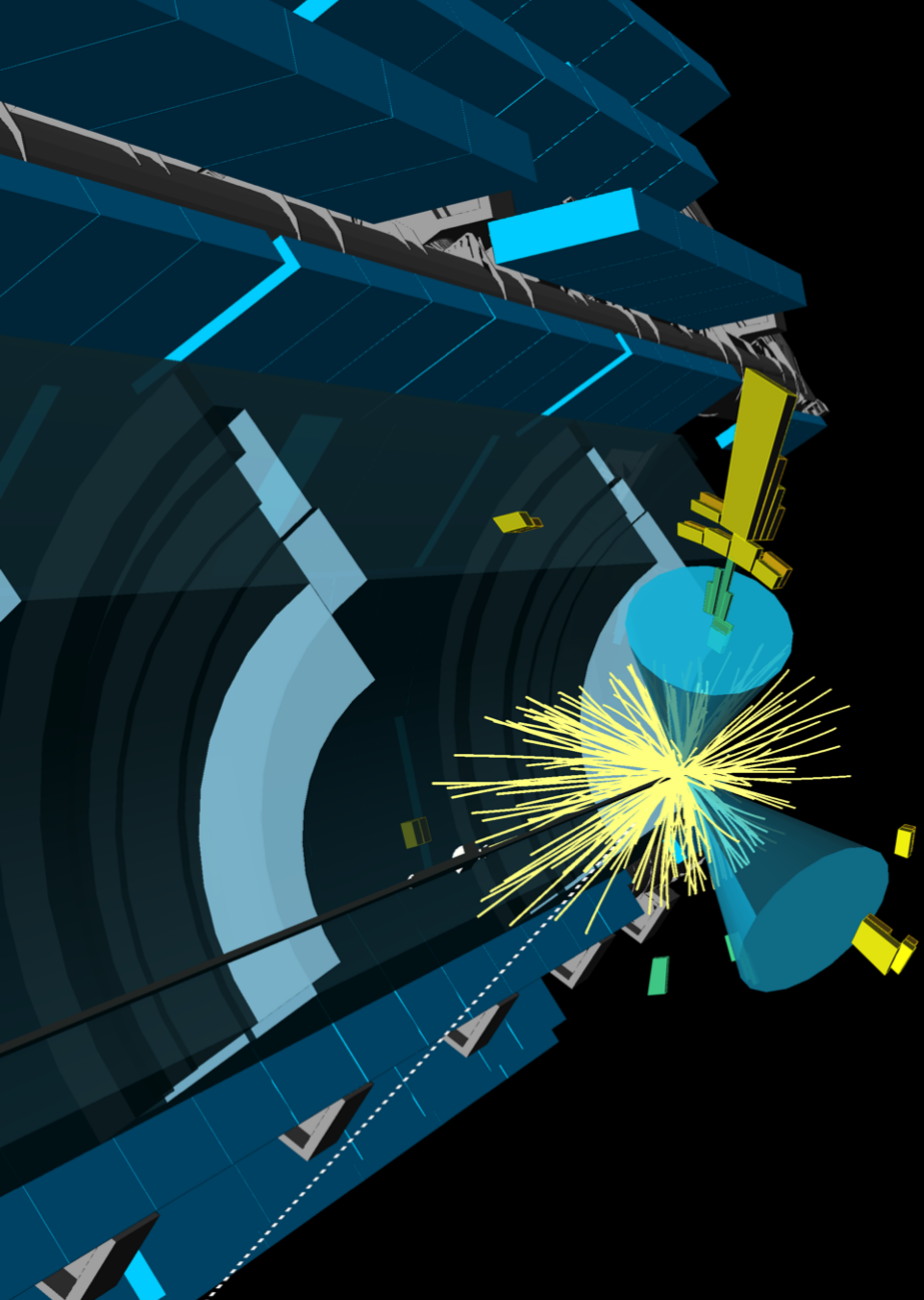


Measurements of Higgs Boson coupling properties to bottom and charm quarks with the ATLAS detector

Marion Missio,
on behalf of the ATLAS collaboration

Higgs 2024 - 6 November 2024

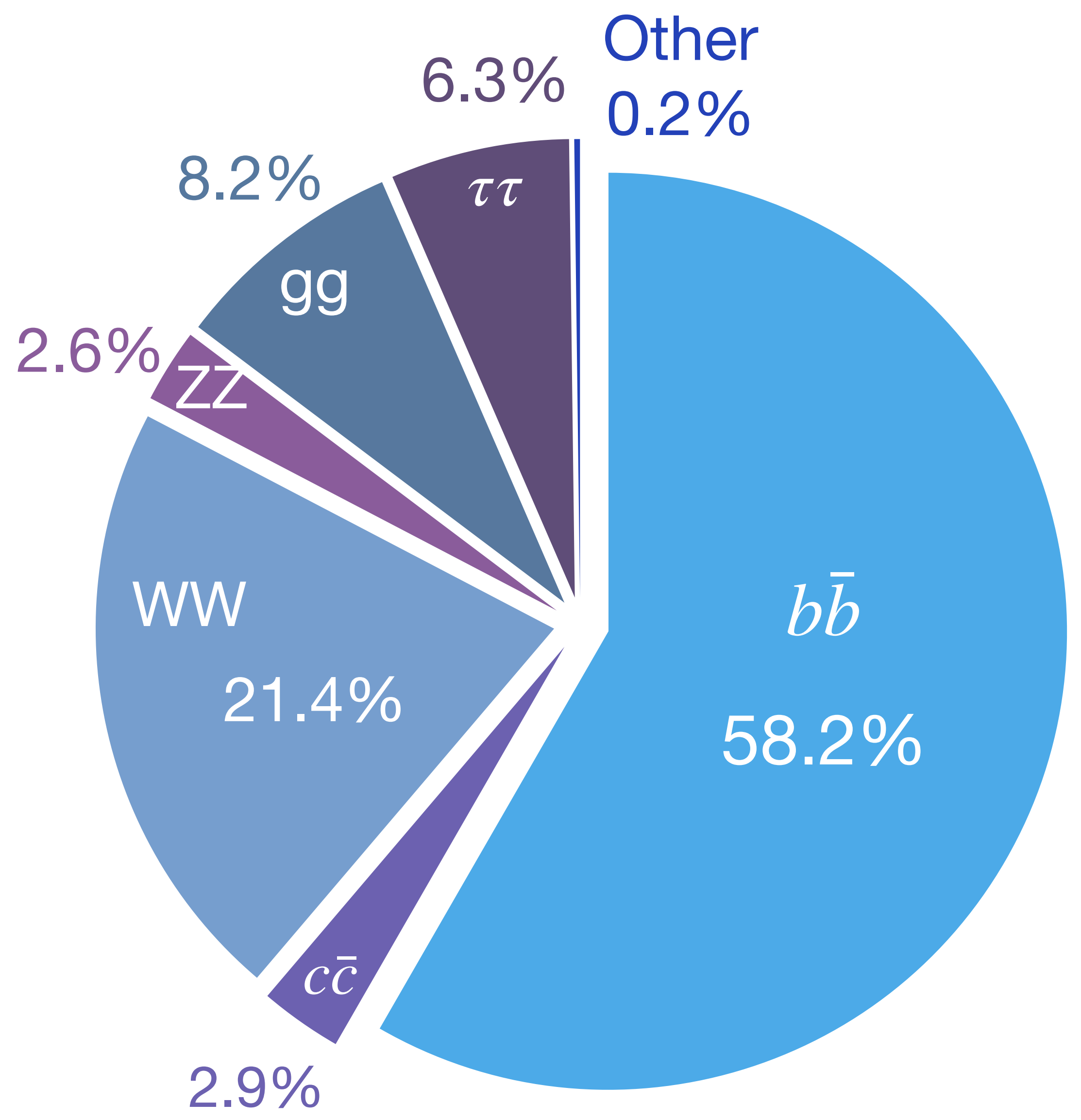
ATLAS EXPERIMENT

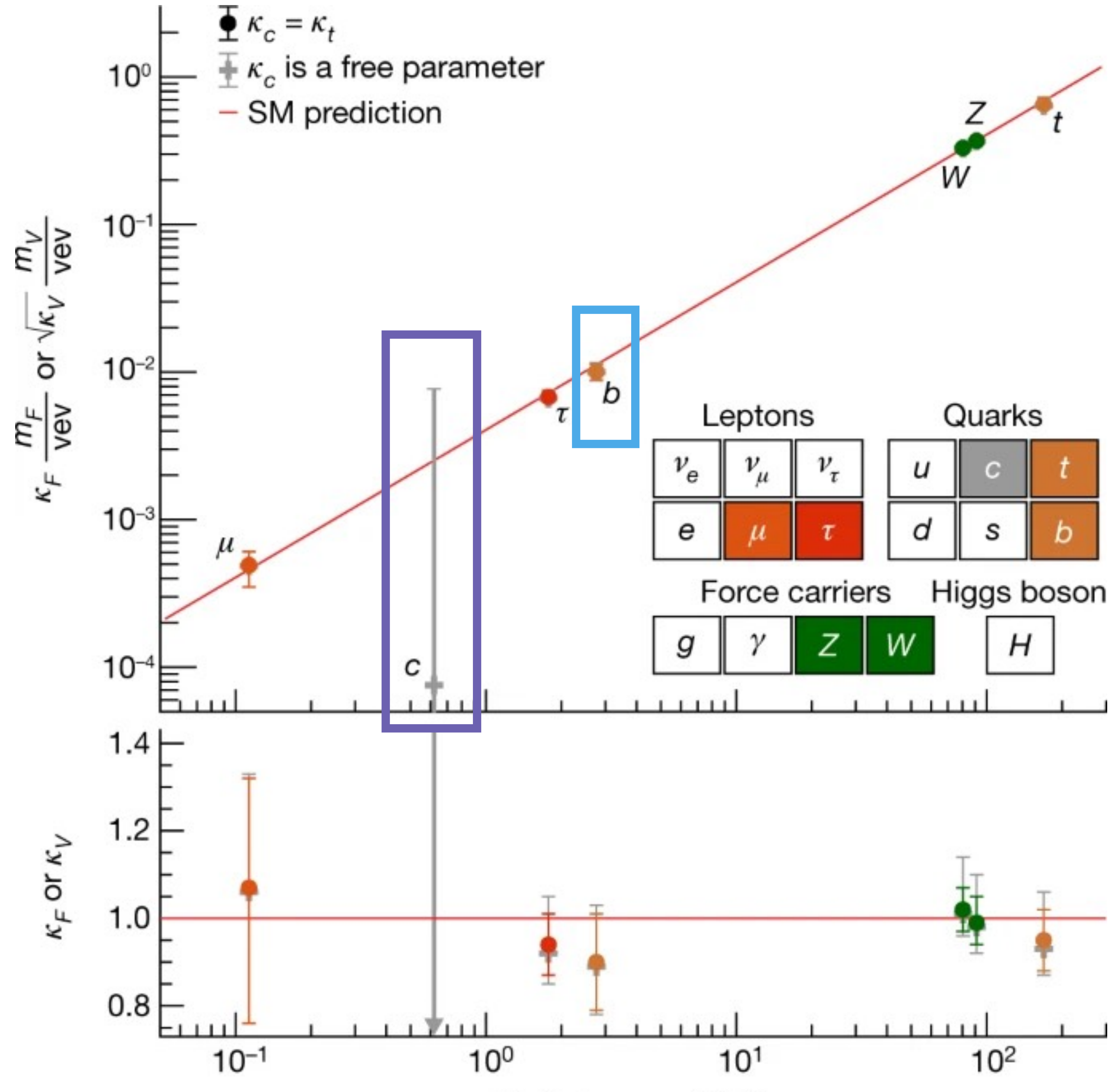
Nikhef

IN·DEI·NOMINE·FELICITER

Introduction

- Since its discovery in 2012, the Higgs boson is being investigated:
  - Important to understand its properties
  - Essential for testing the Standard Model → any deviations could be a hint for new physics
- One key aspect is to measure Yukawa couplings to fermions:
  - b → largest branching fraction, becoming a precision measurement
  - c → challenging, not observed yet

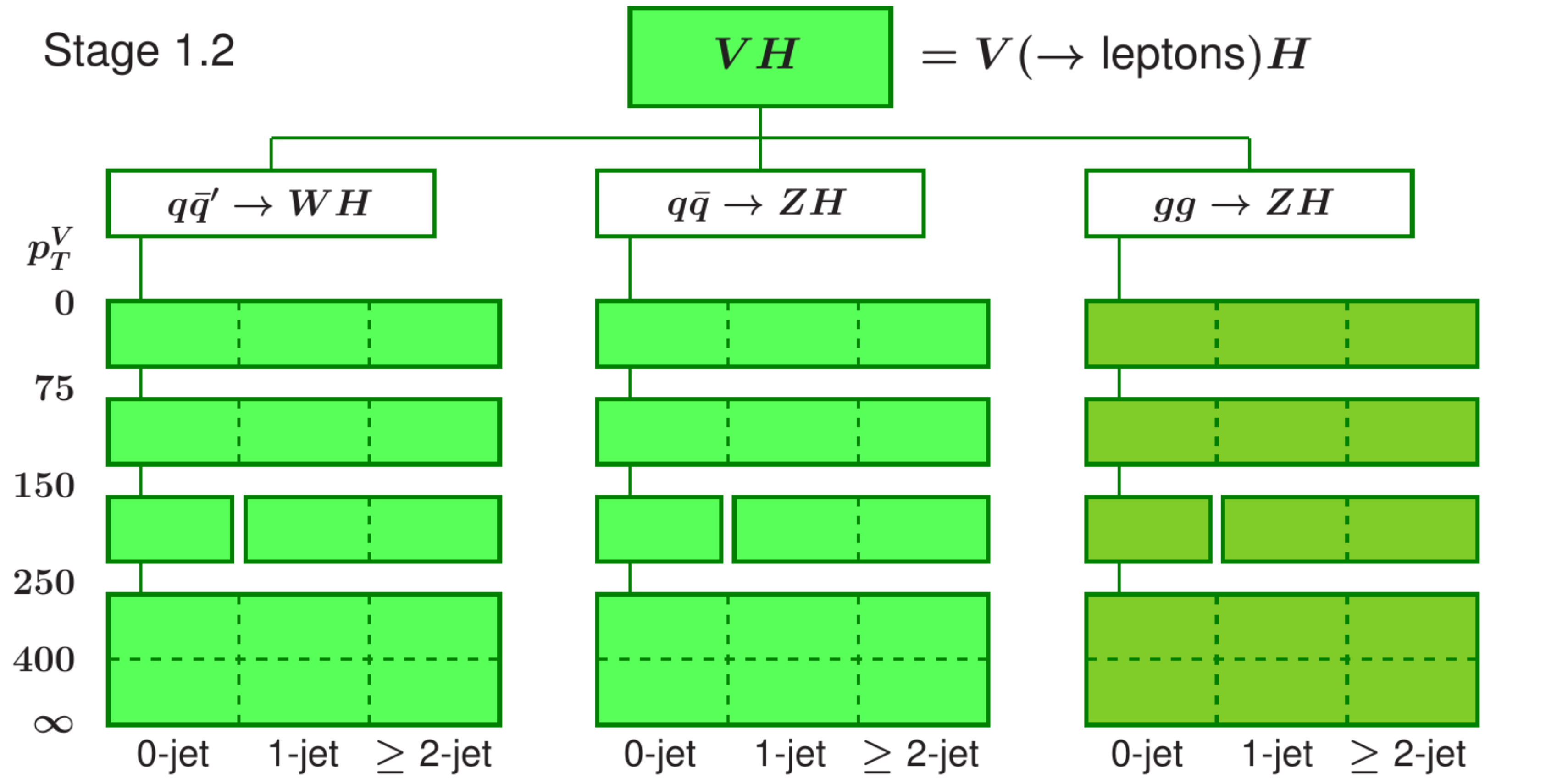


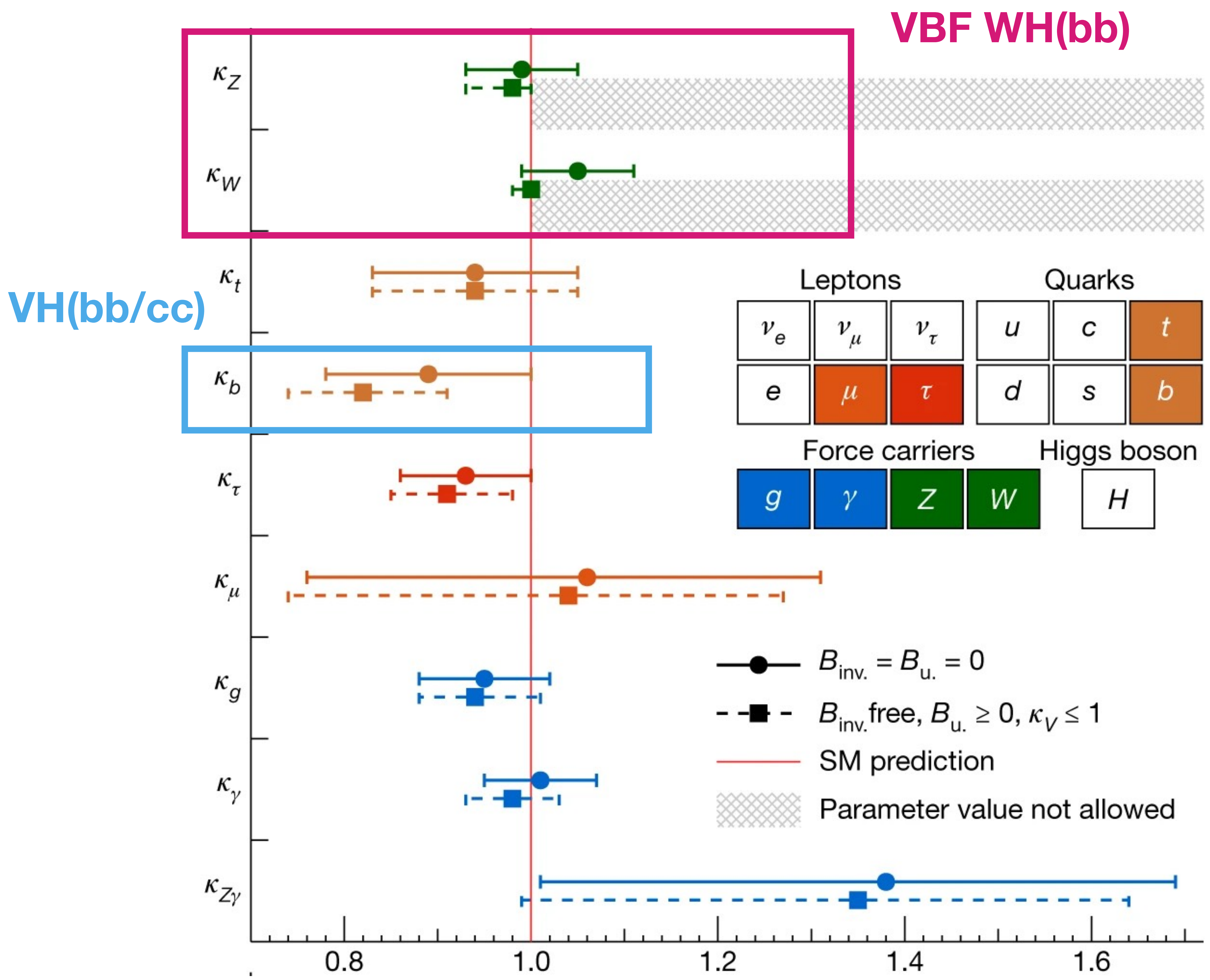


Nature 607, 52–59 (2022)

Introduction

- Many measurements can be conducted with the Higgs boson, such as:
  - Signal strength
  - Cross-section and differential measurement using Simplified Template Cross Sections (STXS)
- Additionally, various interpretations can be performed, including:
  - Yukawa coupling, coupling modifiers (κ)
  - EFT





Nature 607, 52–59 (2022)

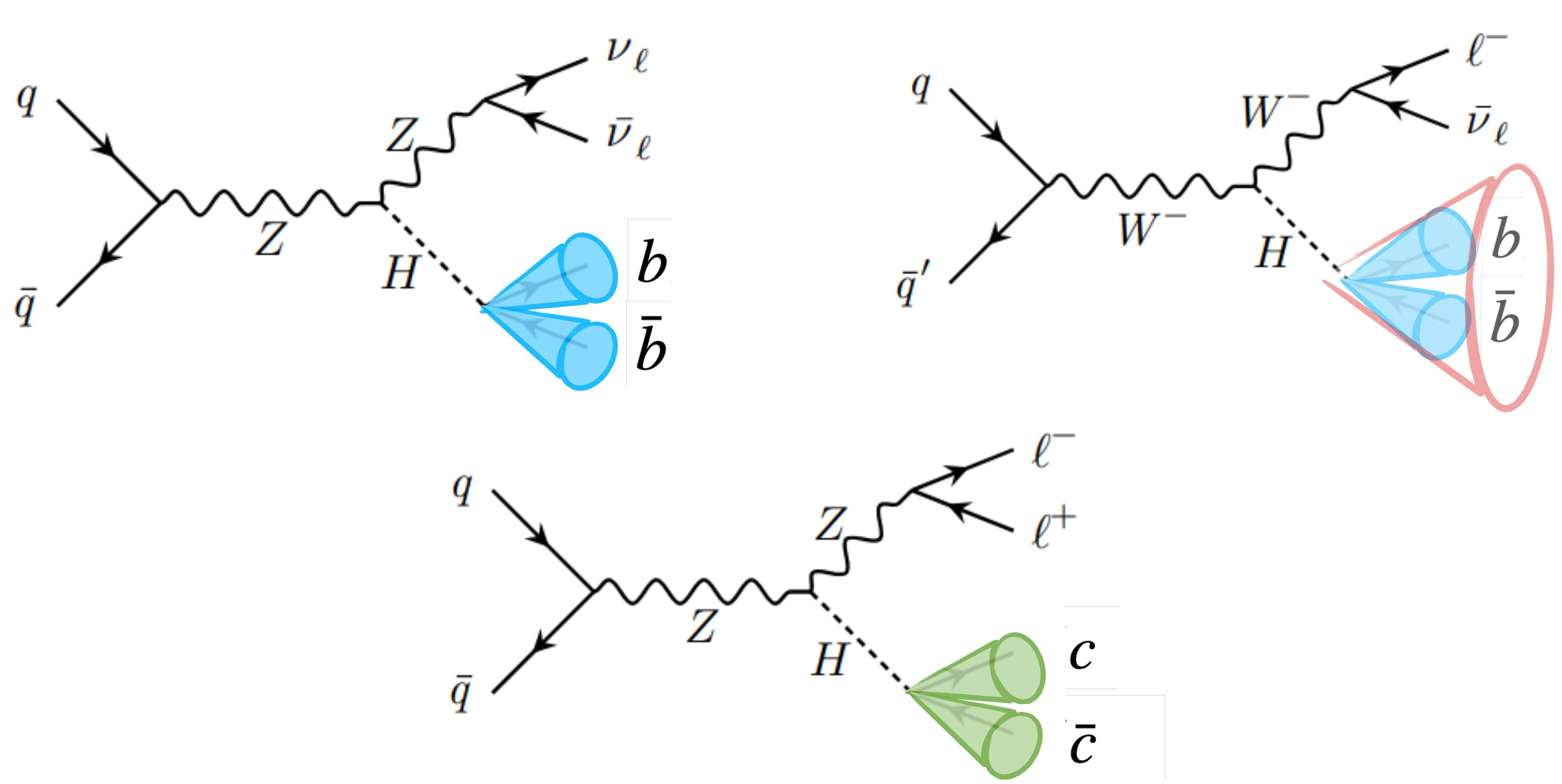
CONF-Note → **06/2024** ; Paper → 10/2024

2410.19611

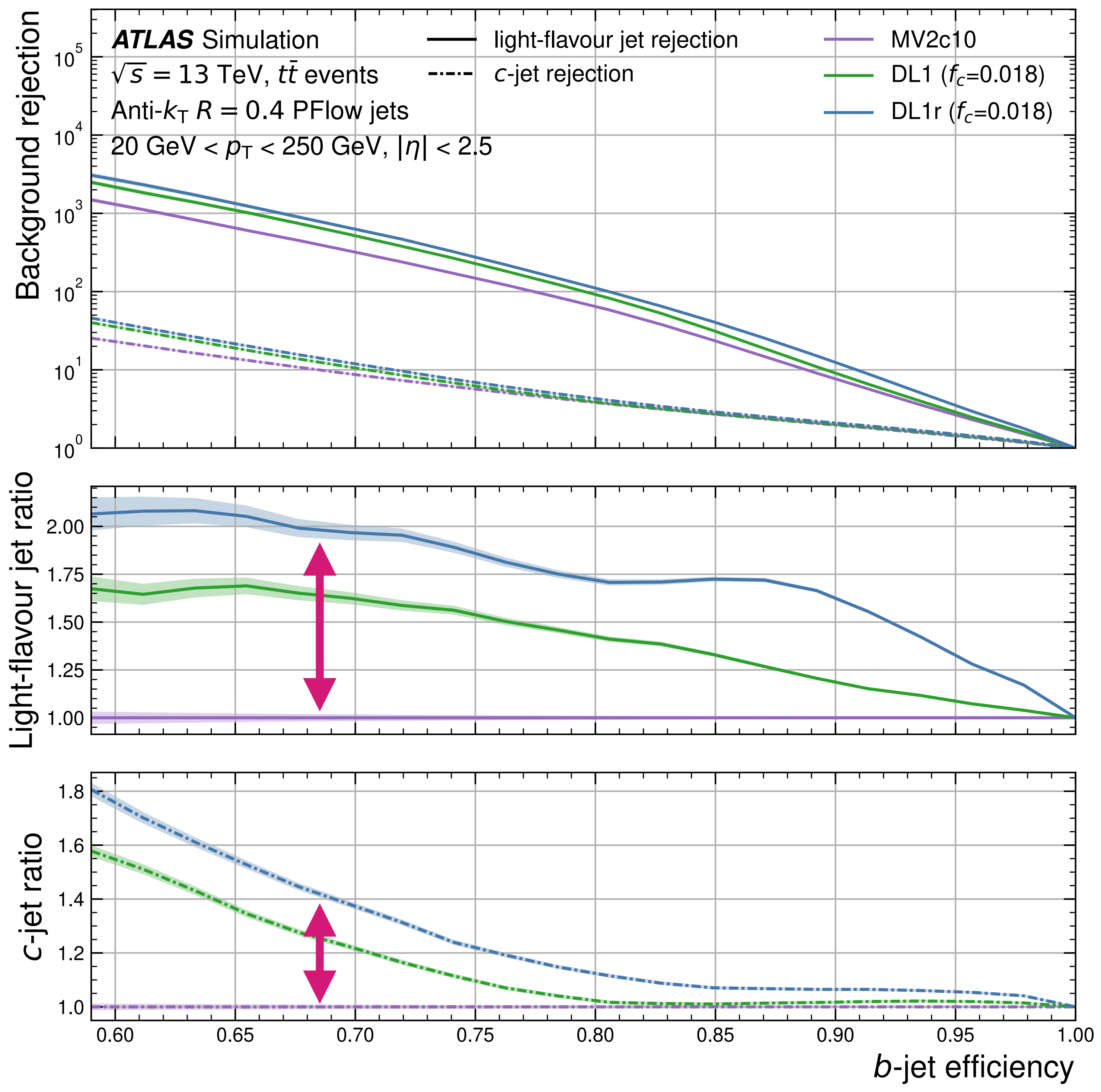
VH(bb/cc)

Motivation

- **Simutaneous measurement of VH(bb) and VH(cc)**
  - VH(bb) split at 400 GeV between resolved and boosted
  - 3 lepton channels: $Z \to \nu\nu$, $W \to l\nu$ and $Z \to ll$
- Re-analysis of full Run2 with **significant changes:**
  - Improved flavour tagging with DL1r → gives probability of jets coming from b-, c- or light-quark
  - First use of BDT for VH(cc) and boosted VH(bb)
  - New MC samples and increased statistics for alternative samples
  - Different analysis regions



EPJC 83,681



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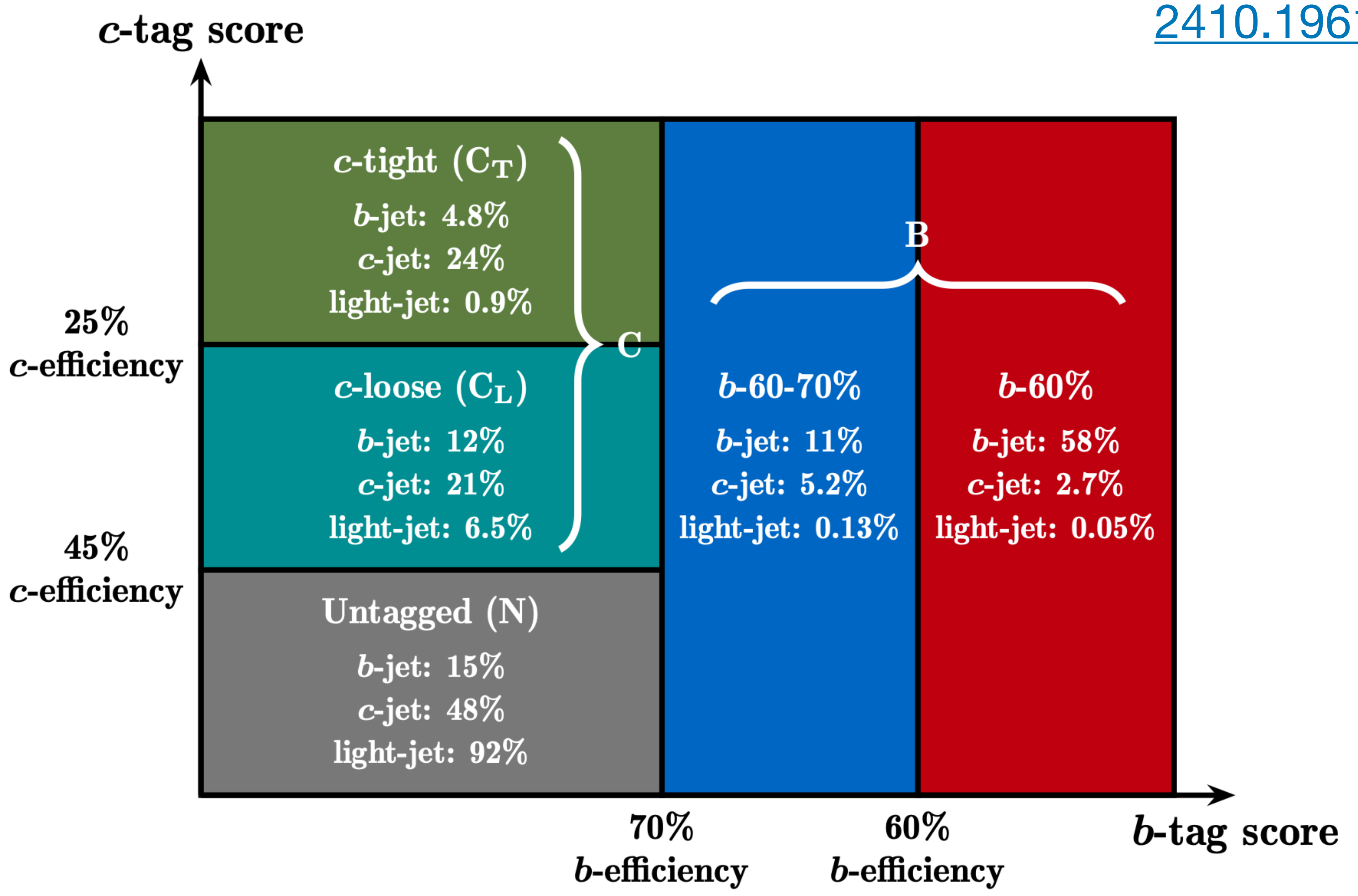
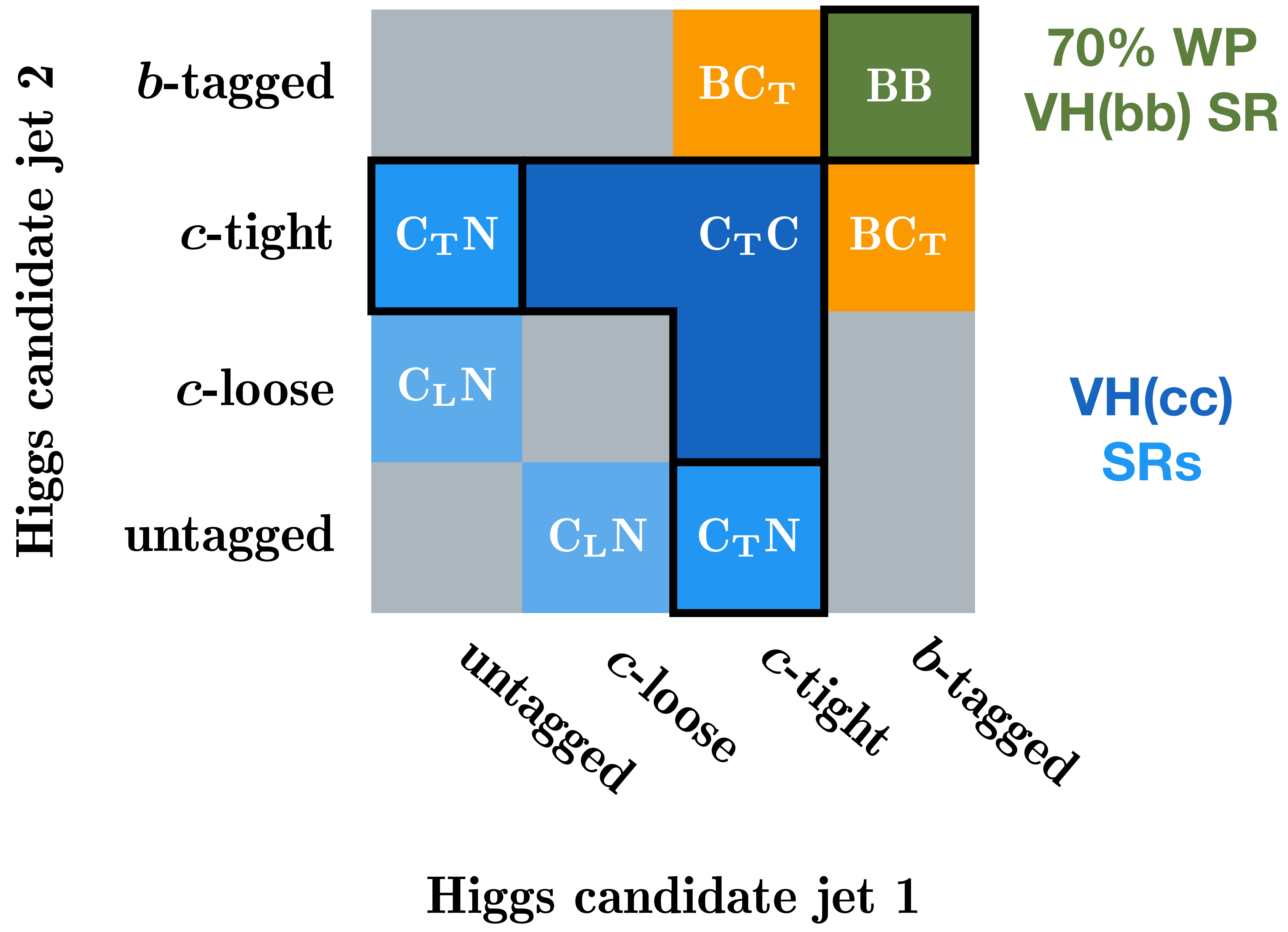
VH(bb/cc)

Flavour tagging

- Harmonised approach of b- and c-tagging:
  - 2D pseudo-continuous scheme
  - c-tagging bins were optimised for this analysis
- Dedicated control regions to constrain V+jets $(C_L N)$ and Top (BC_T)
  - Minor backgrounds: multijet, single top and diboson
  - Also CR defined by continuous cut on $\Delta R(j_1, j_2)$
- Boosted VH(bb): only b-tagging → 85% WP b-tag SR and 1 top CR





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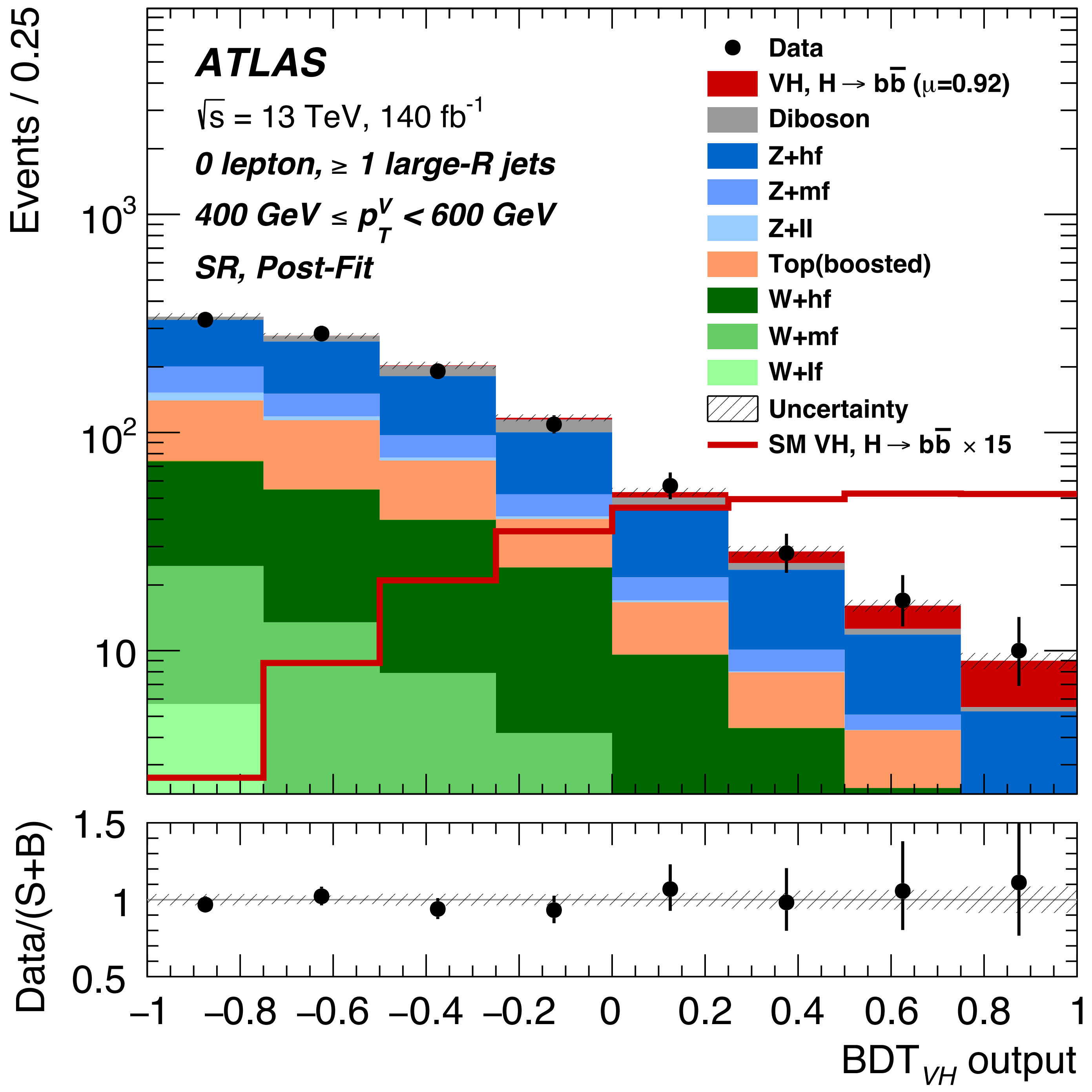
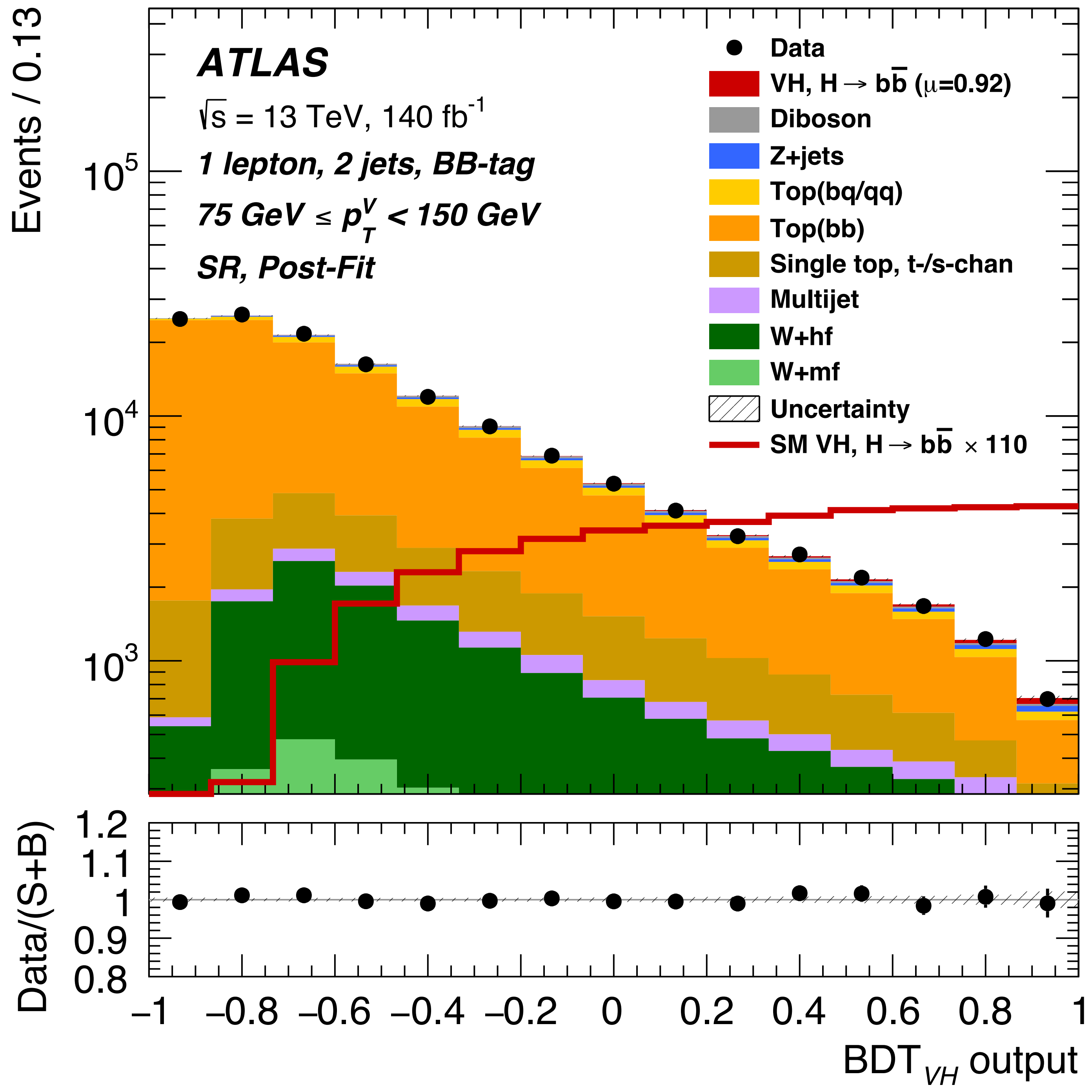
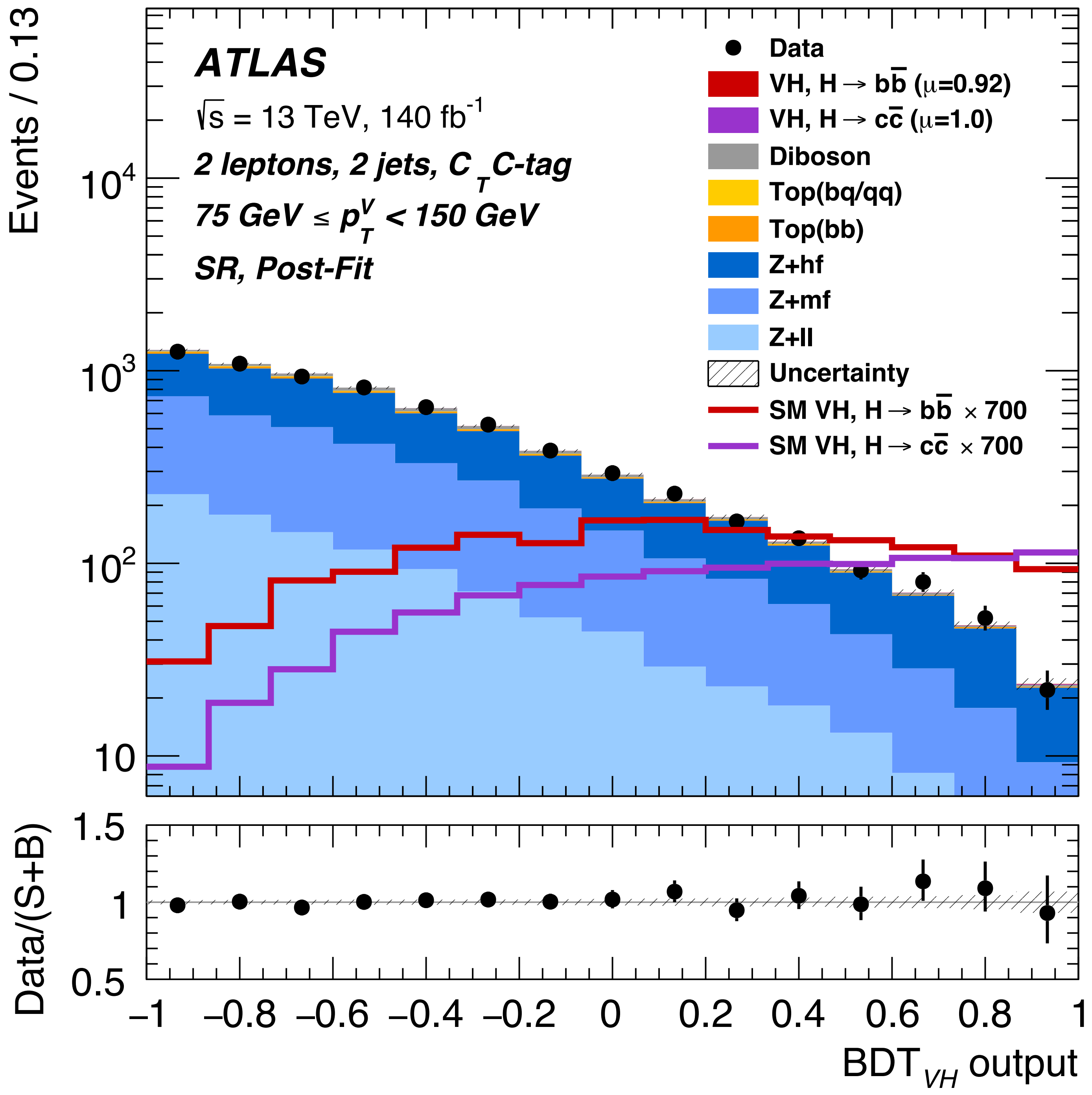
VH(bb/cc)

BDT

- Use of BDT to discriminate signal from background
- Fully harmonised between VH(cc) and resolved VH(bb) (more details in back-up)
- Improvement up to 30% for VH(cc) and up to 50% for boosted VH(bb)



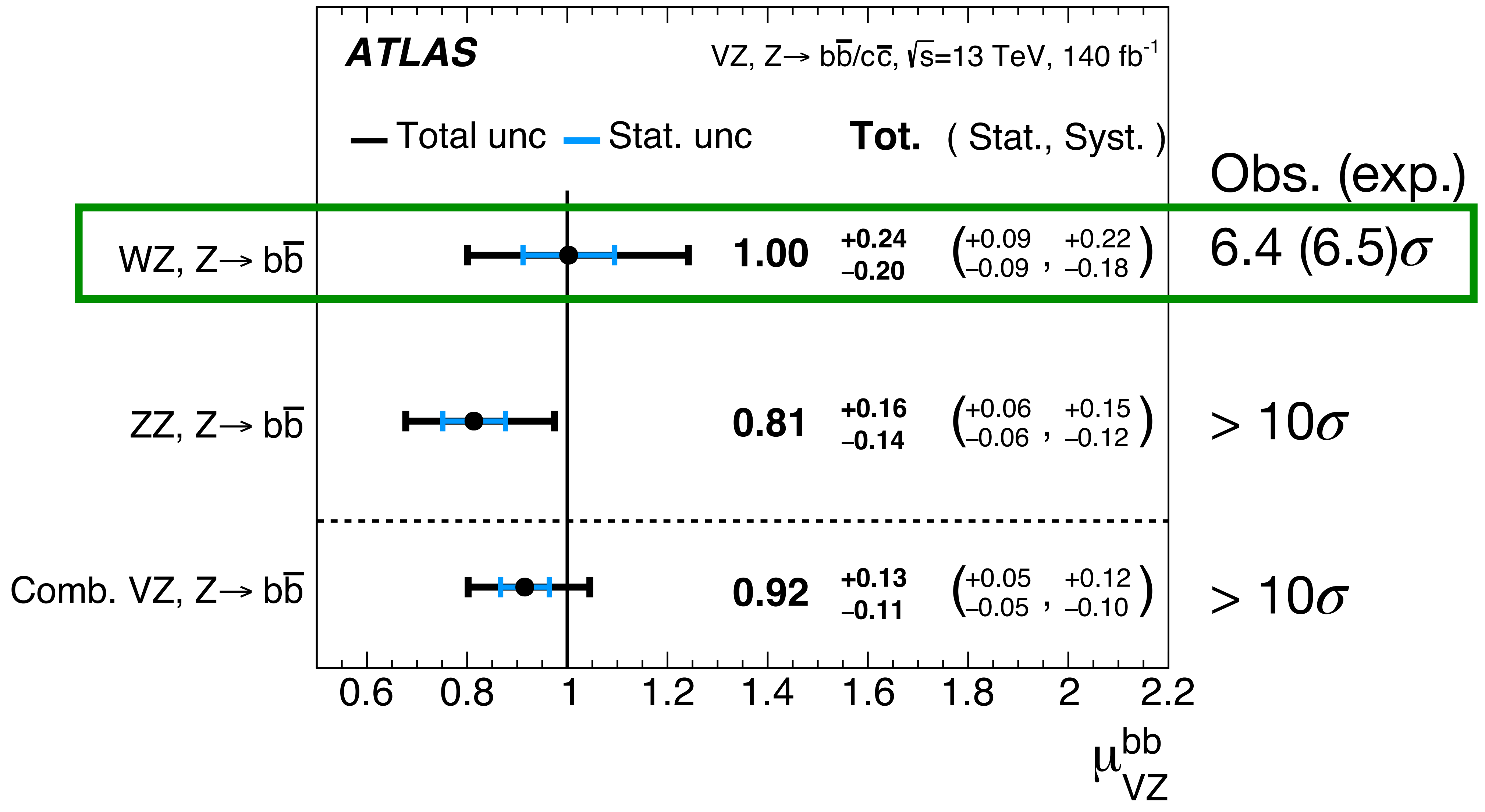


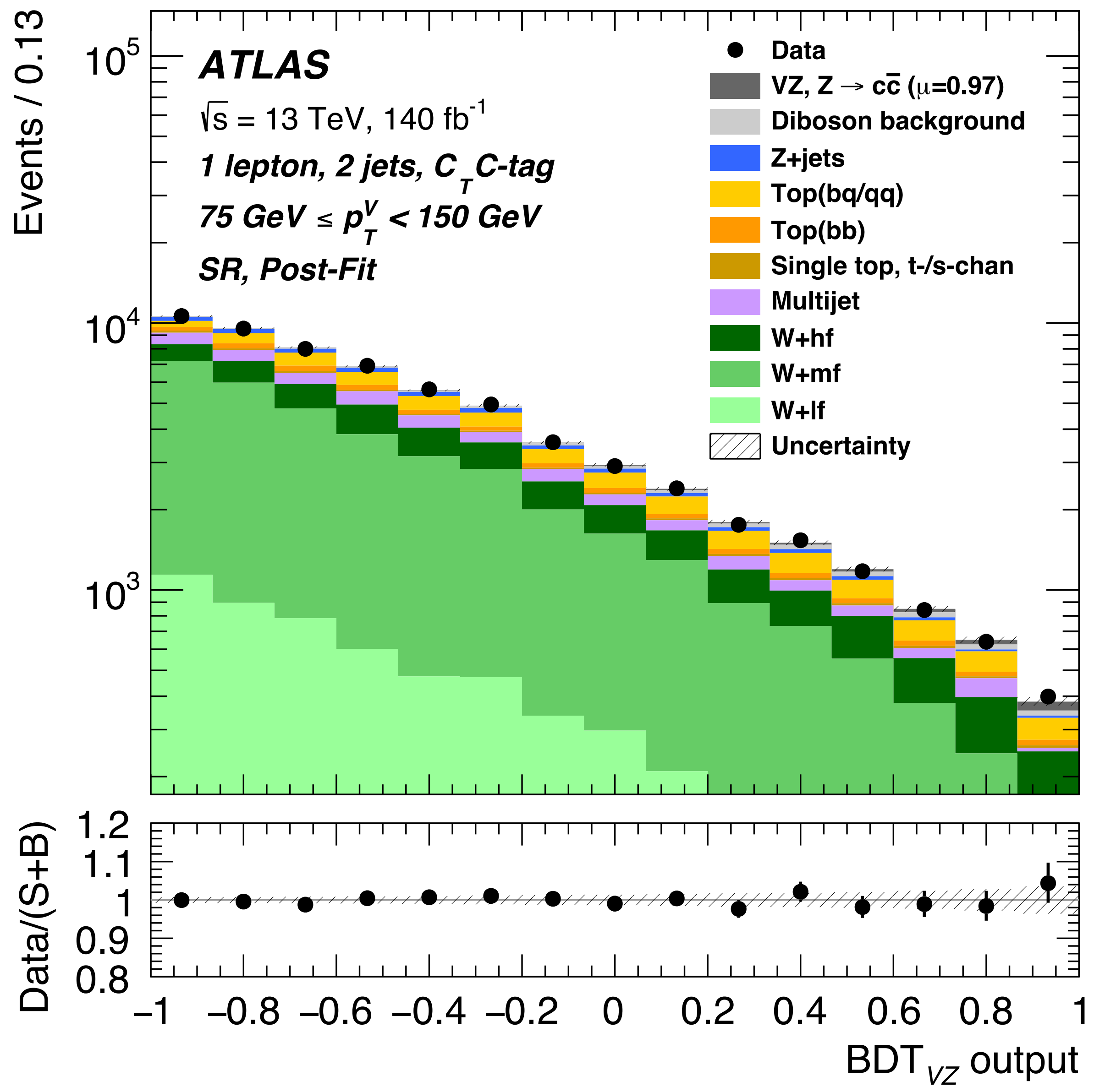


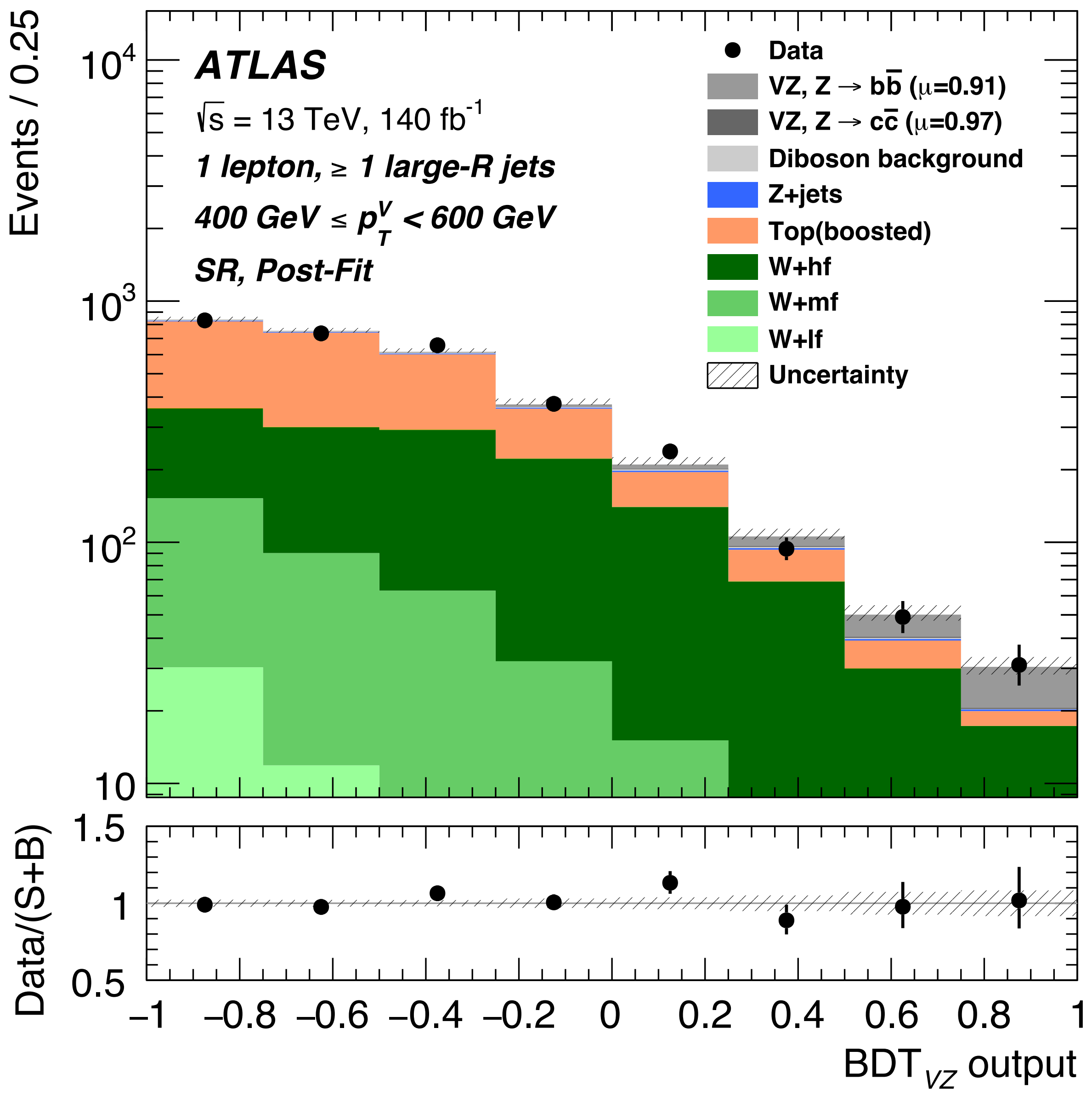
VH(bb/cc)

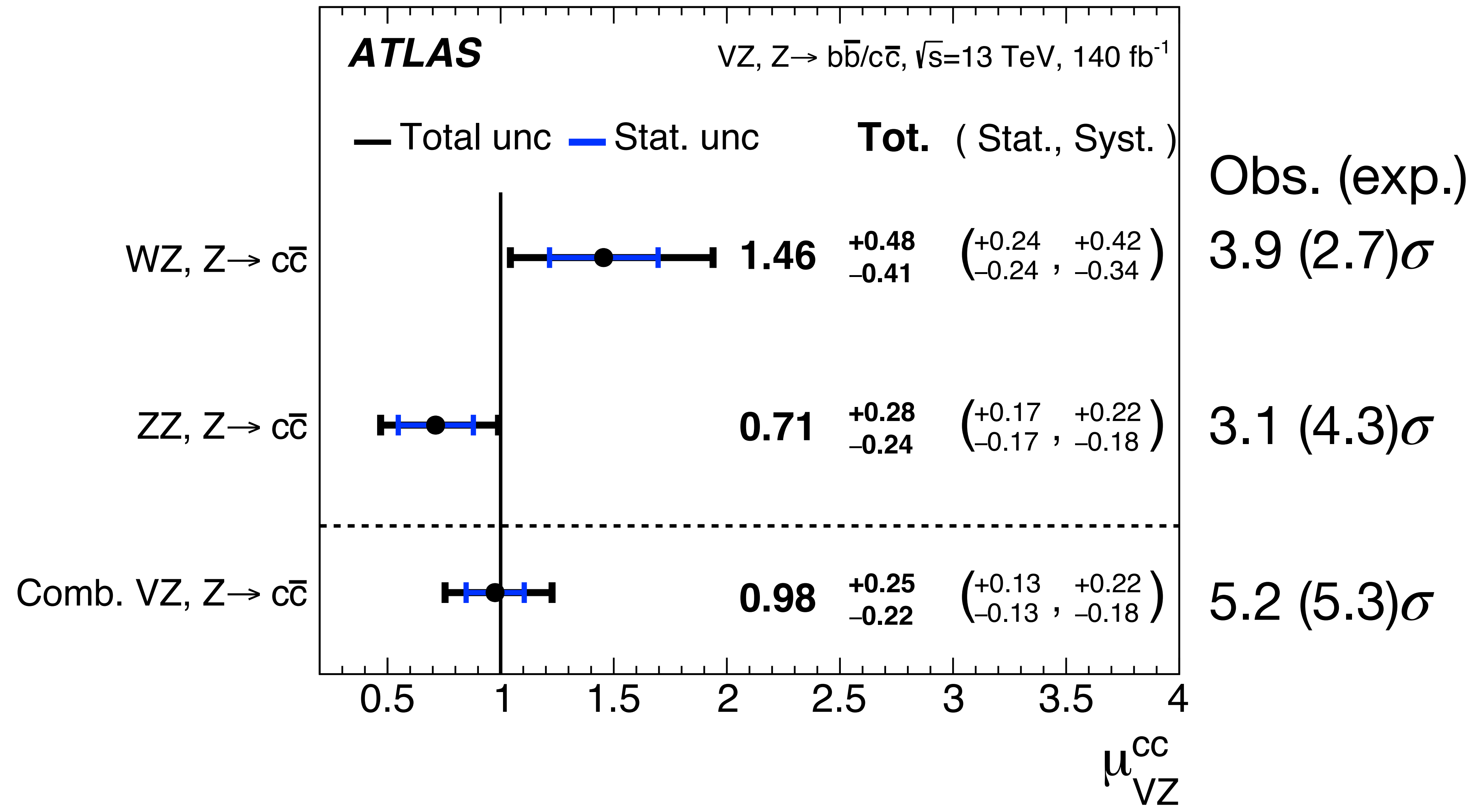
Diboson cross-check

- Use similar signature of VZ processes to validate the analysis strategy:
    - Only difference: BDT trained with VZ as signal
    - **First observation for WZ(bb)! First ATLAS observation for VZ(cc)**







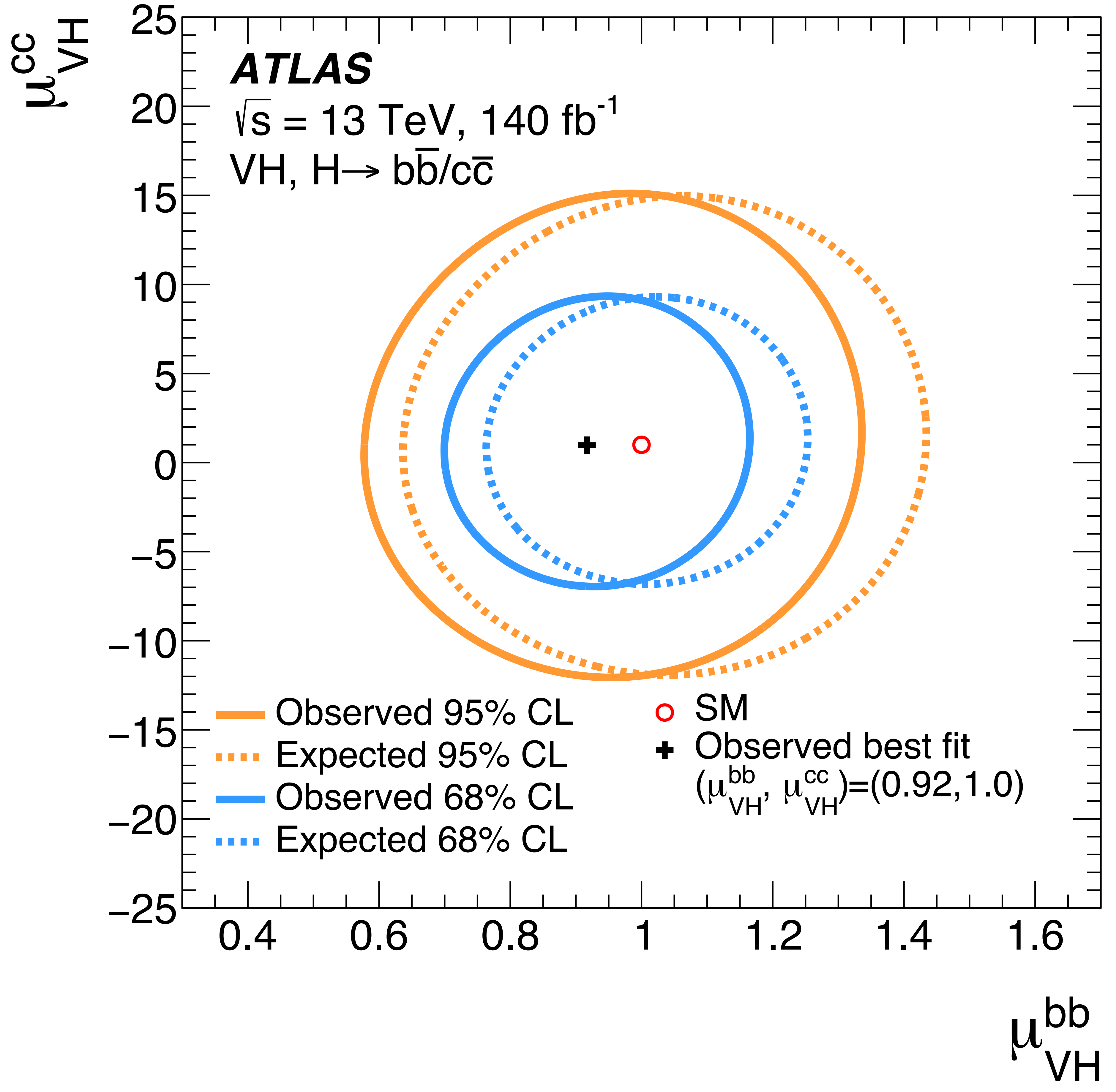


VH(bb/cc)

Results: Signal strengths

- **Simultaneous measurement** of VH(bb) and VH(cc) signal strengths:

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

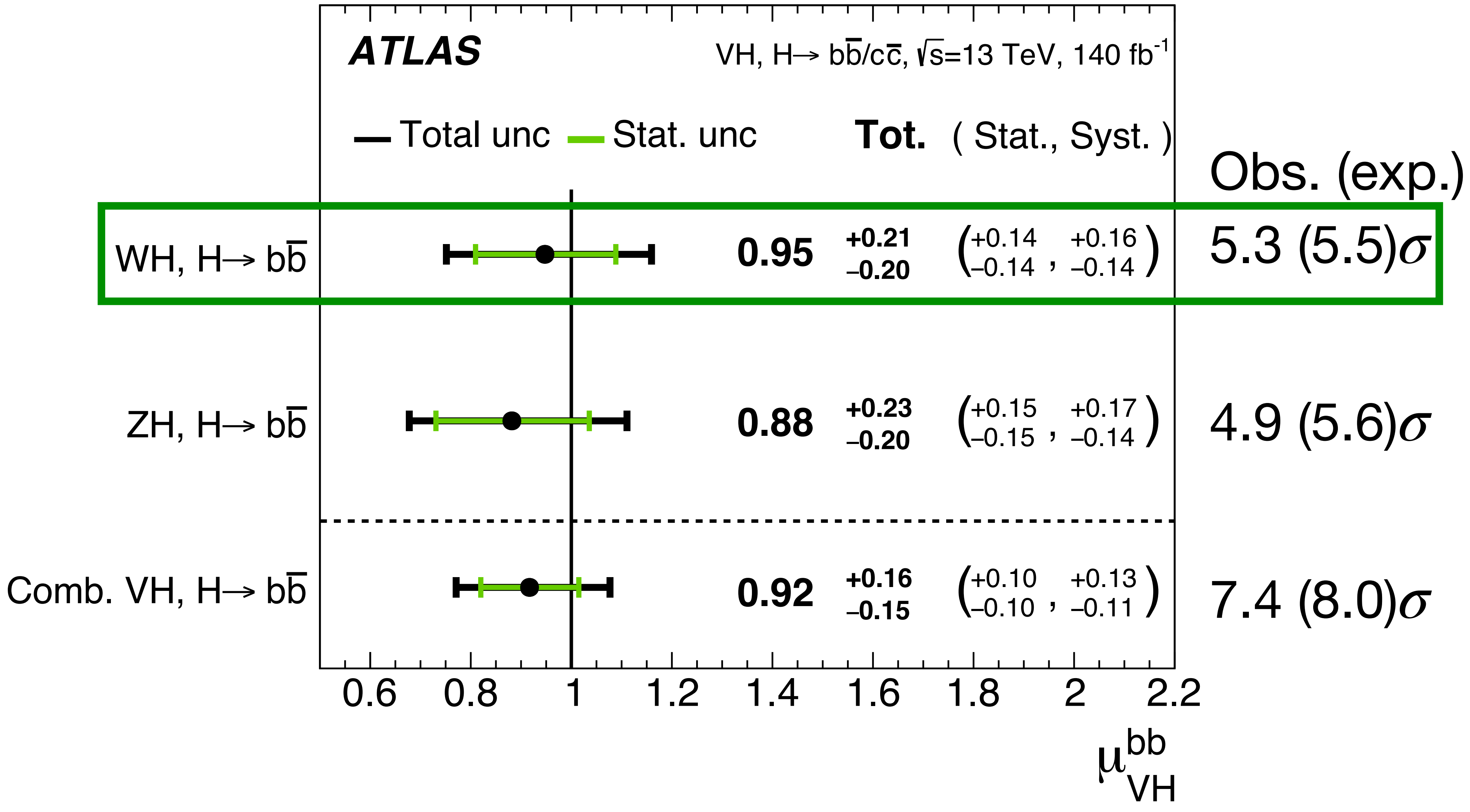


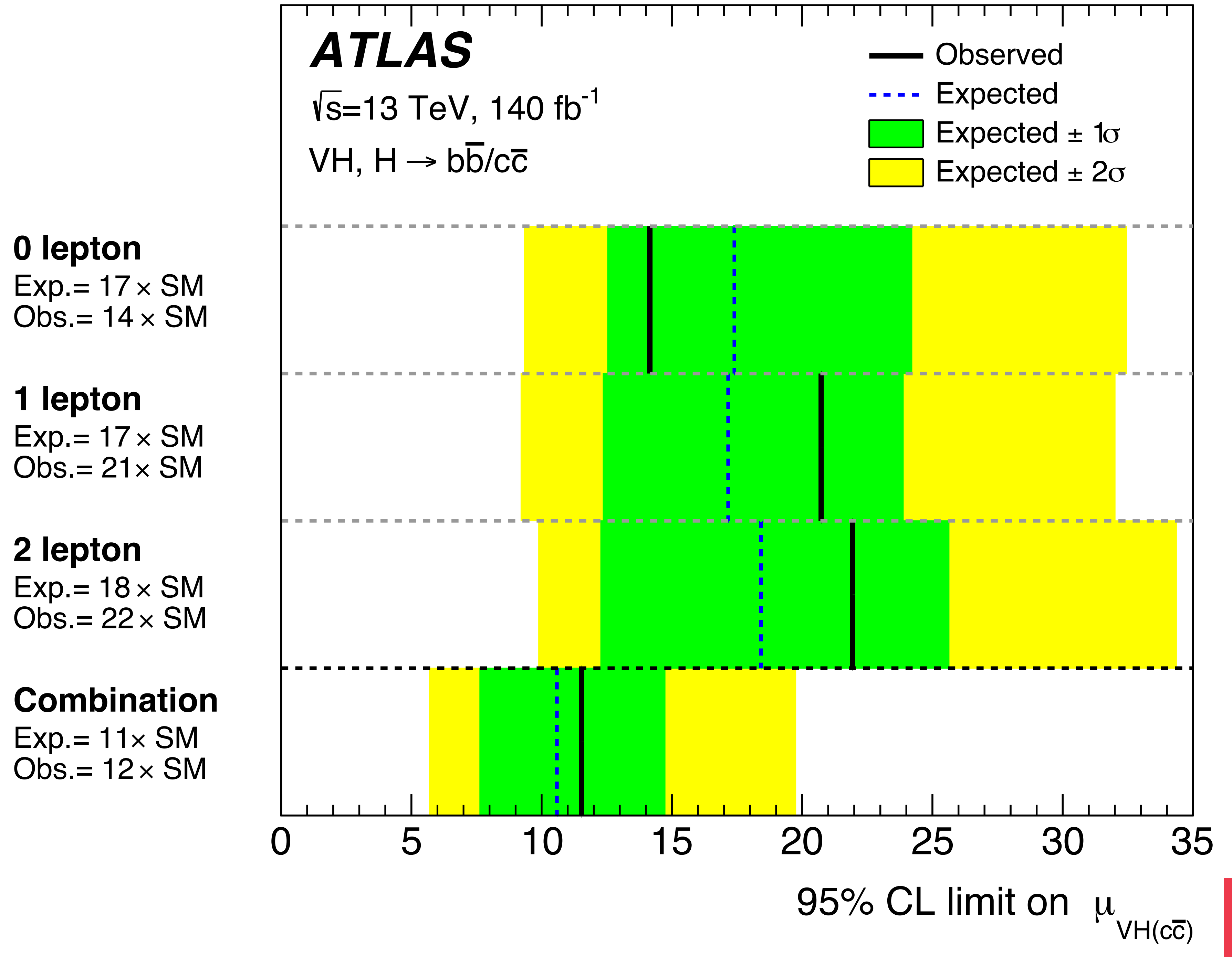
- Correlation between signal strengths is +5%
- Good agreement with the SM predictions

VH(bb/cc)

Results: Signal strengths

- VH(bb): **first observation of WH(bb)!**
    - **23%/10% improvement for WH/ZH** on total uncertainties compared to previous analysis
    - Improvement due to increased c-jet rejection, re-optimisation of BDT, etc.
- VH(cc) limit at 95% CL: <11.5 (10.6) → **~3 times better** than first full Run2 analysis
    - Improvement mainly due to optmised flavour tagging and use of BDT

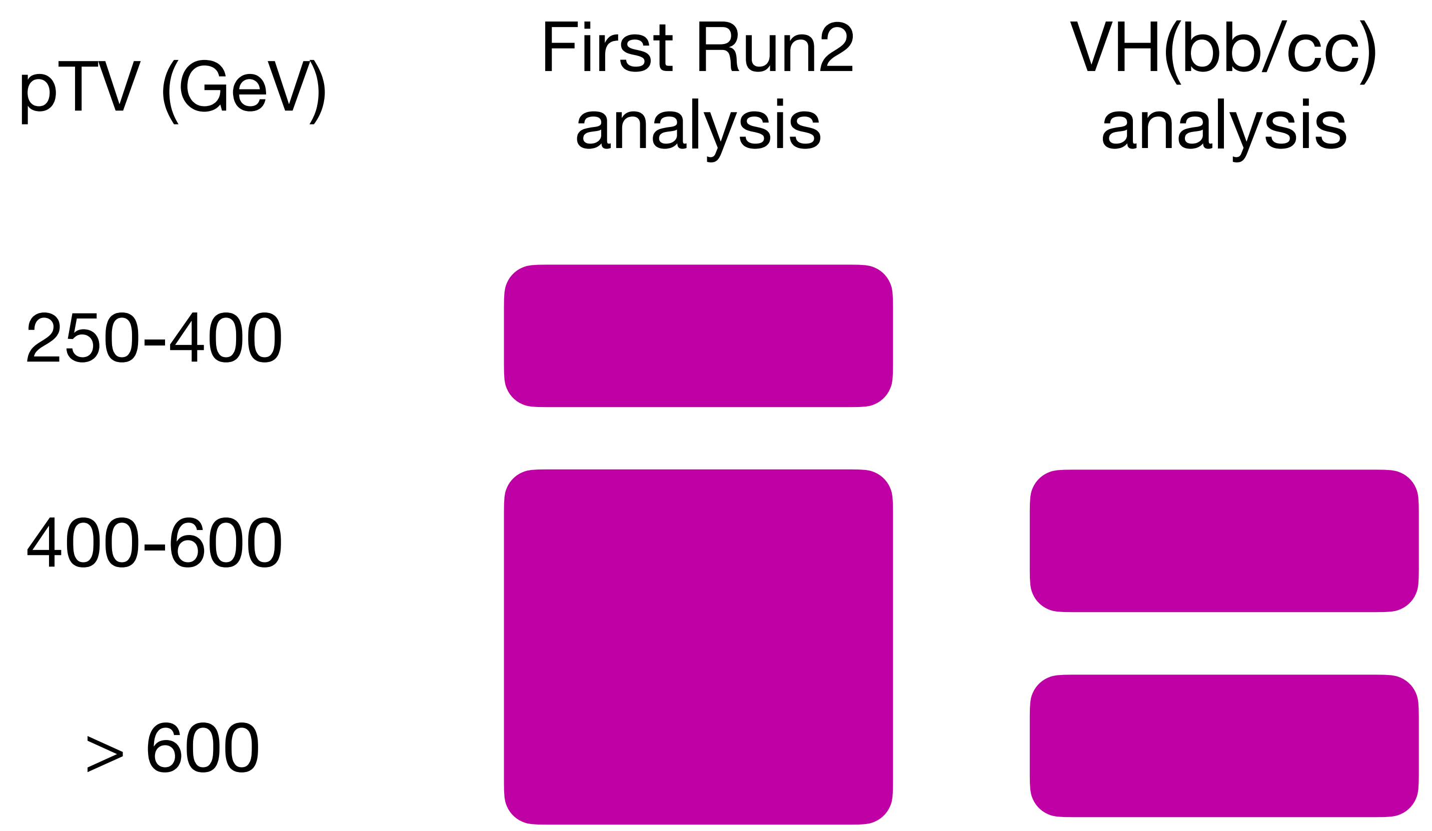




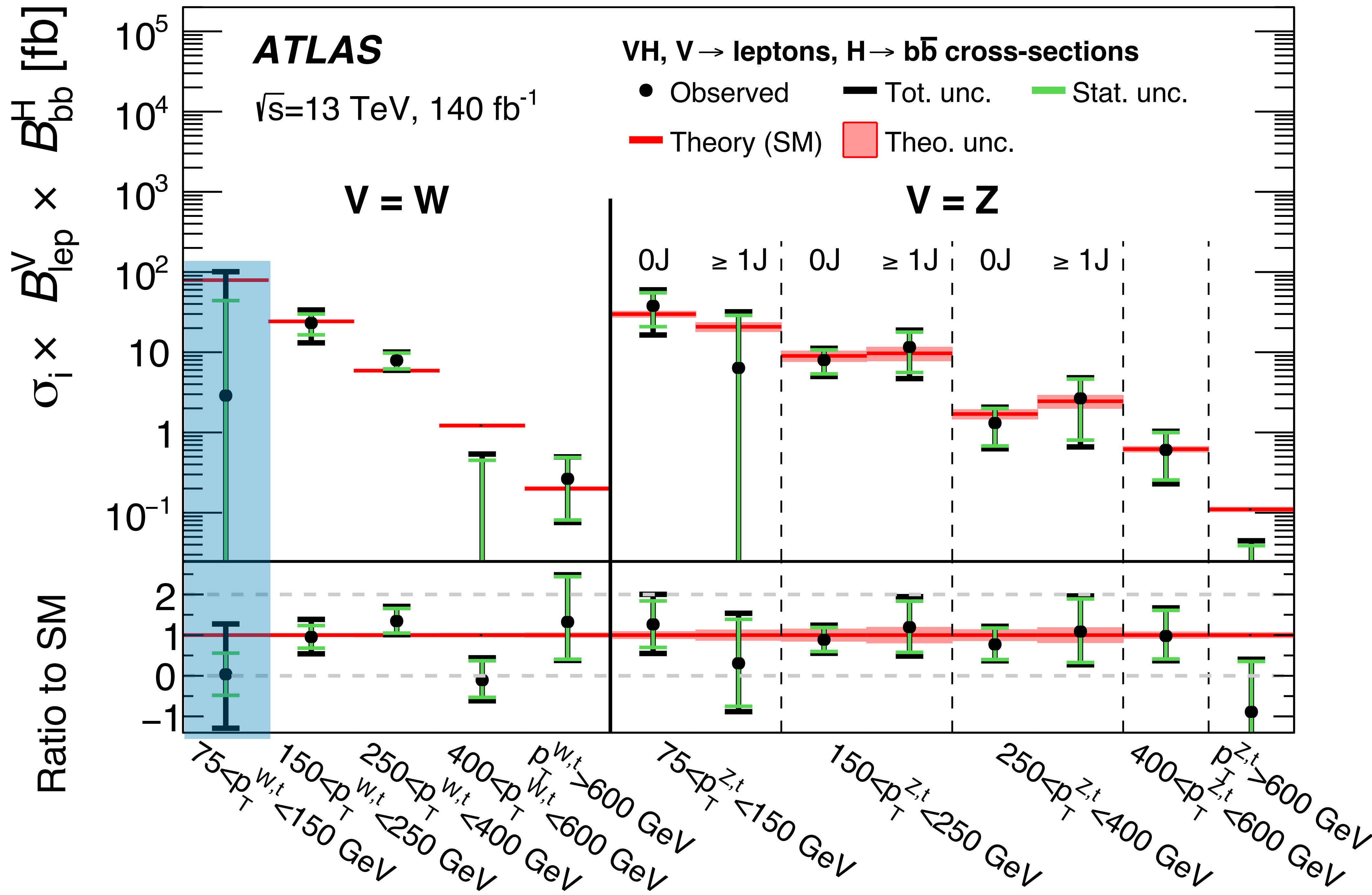
VH(bb/cc)

Results: STXS measurement

- Differential STXS cross-section measurement only for VH(bb) :
  - New 75-150 GeV region for WH and different boosted regions



  - Good agrement with SM predictions → 90% compatibility



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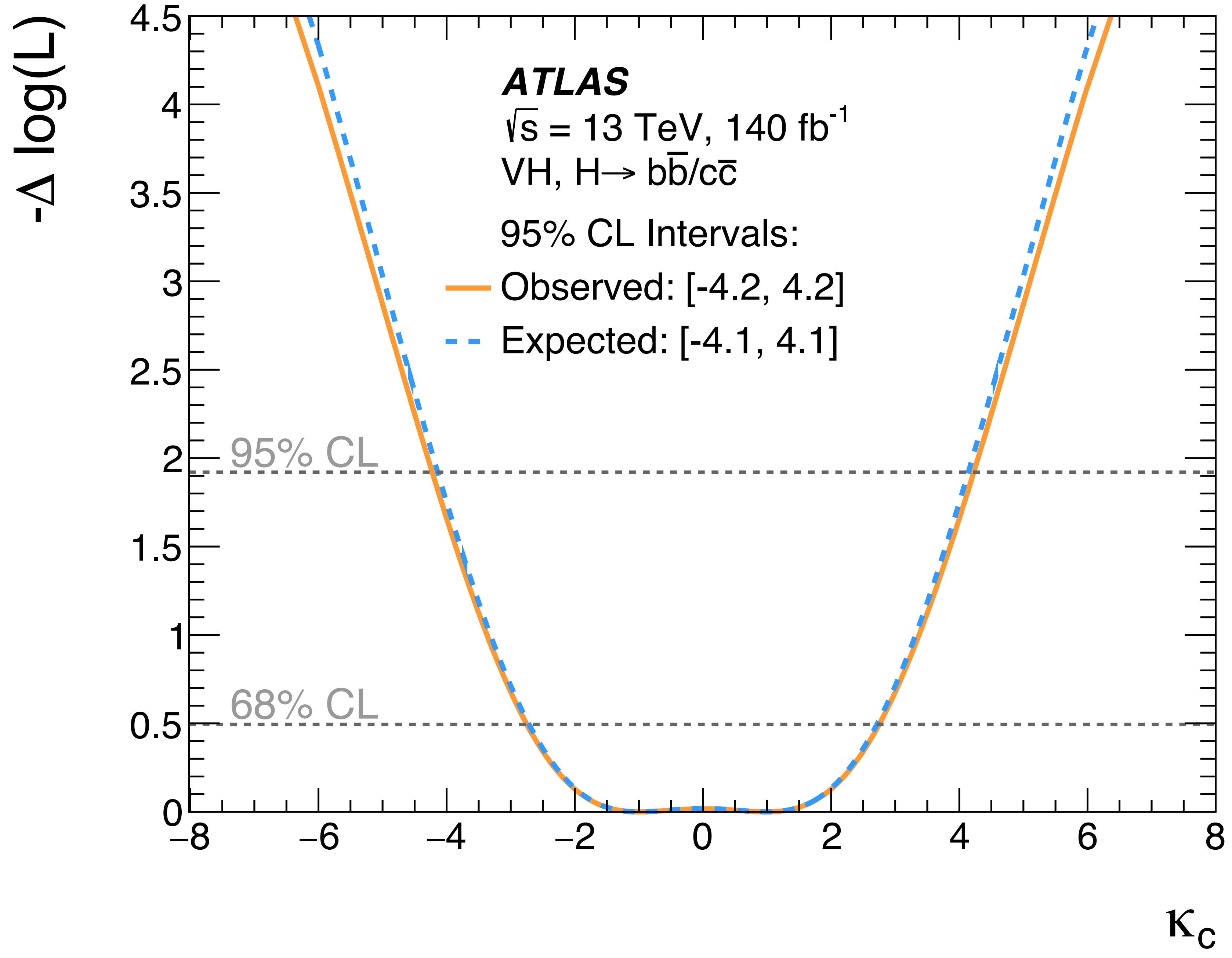
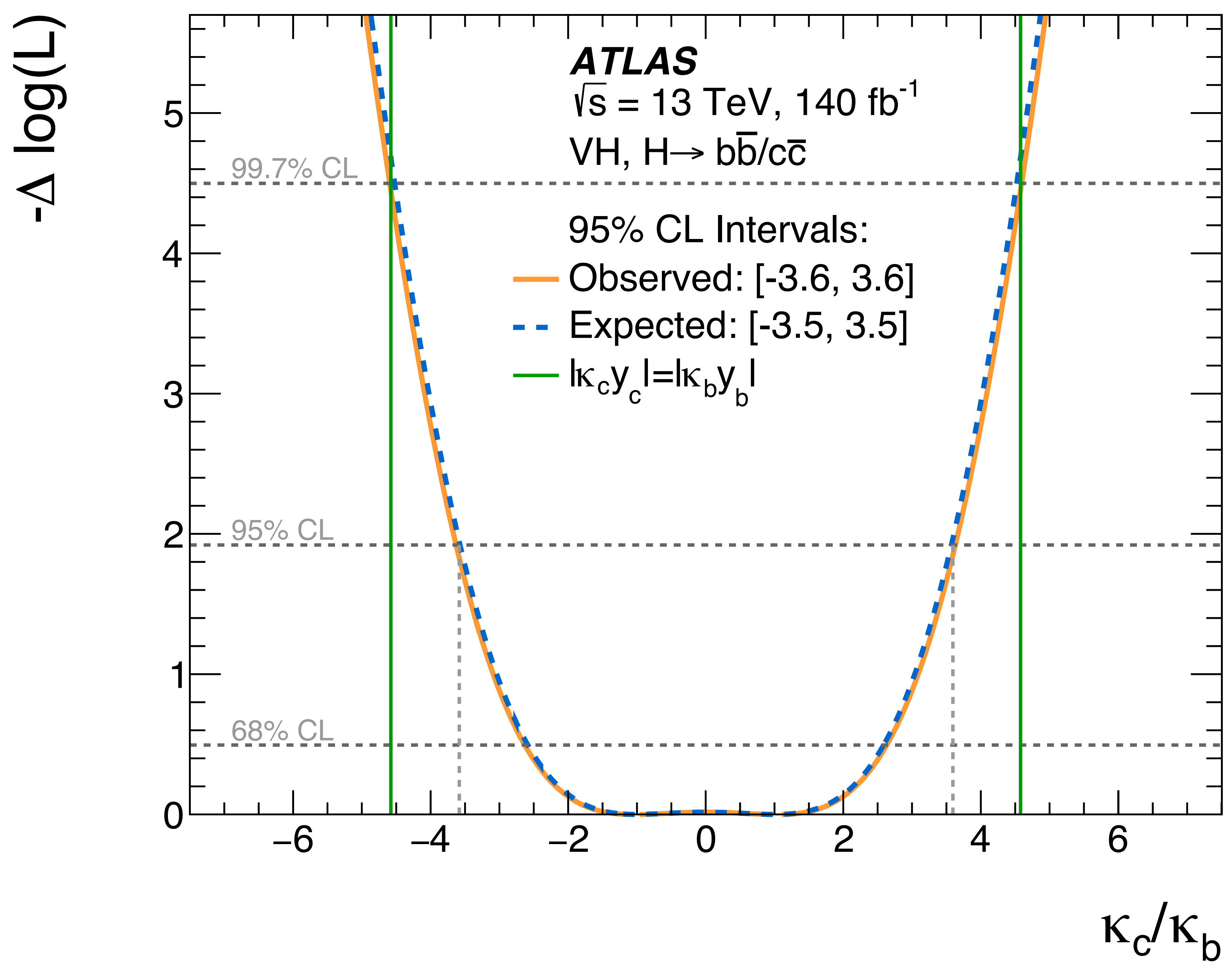
VH(bb/cc)

Results: Higgs couplings

- Signal strength interpreted with coupling modifiers (κ_b, κ_c):
  - Constraint on κ_c: 1D likelihood scan while fixing κ_b to 1 → $|\kappa_c| < 4.2$ at 95% CL
  - 2D scan with κ_b, κ_c left floating
  - Constraint on $|\kappa_c/\kappa_b|$ ratio: no assumptions on Higgs width → **Higgs coupling to charm is weaker than Higgs coupling to beauty at 95% CL**





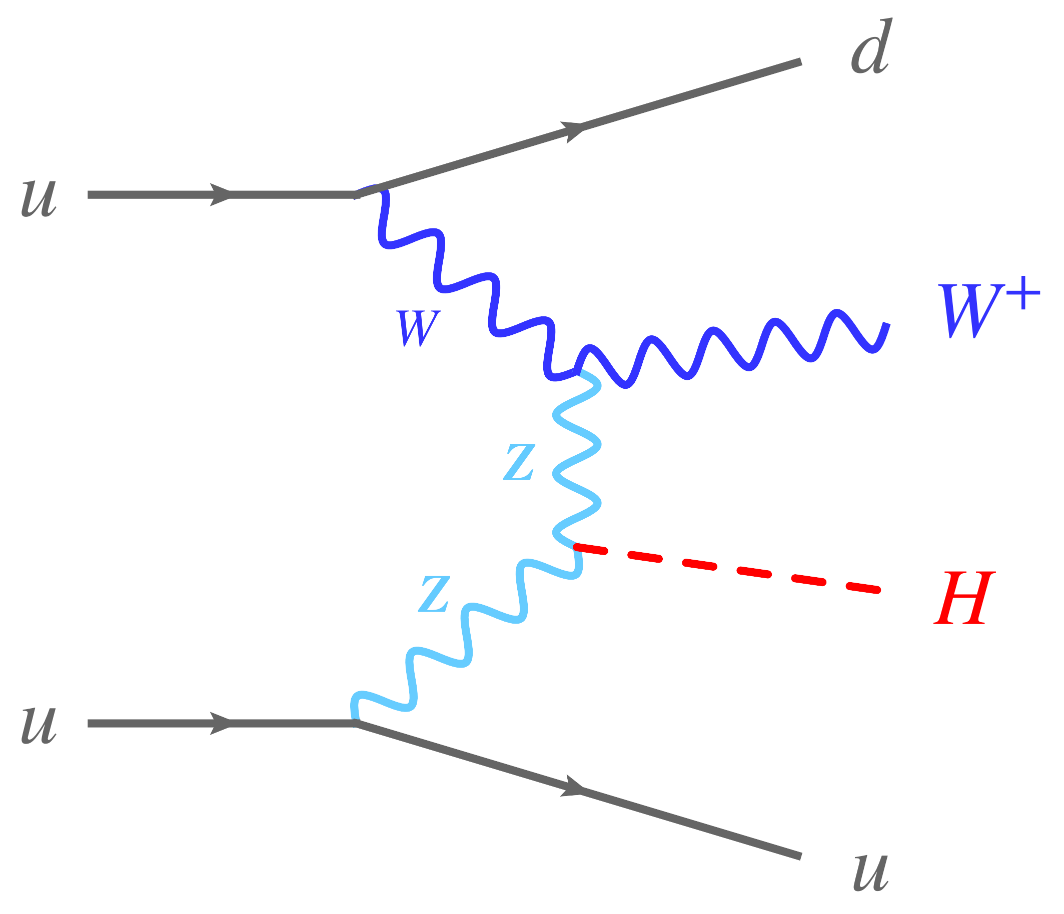
PRL 133.141801

Vector Boson Fusion (VBF) WH(bb)

Motivation

- **First VBF WH analysis** → can use WH(bb) to probe coupling to W/Z bosons
  - Use H(bb) because of large branching fraction
- Unique sensitivity to the relative sign of $|\lambda_{WZ}| = \kappa_W/\kappa_Z$
  - Large cross-section enhancement if $\lambda_{WZ} < 0$ → $\sigma_{\lambda<0} \approx 6\ \sigma_{\lambda>0}$

$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z\,\kappa_W\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z^2\,\lambda_{WZ}\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

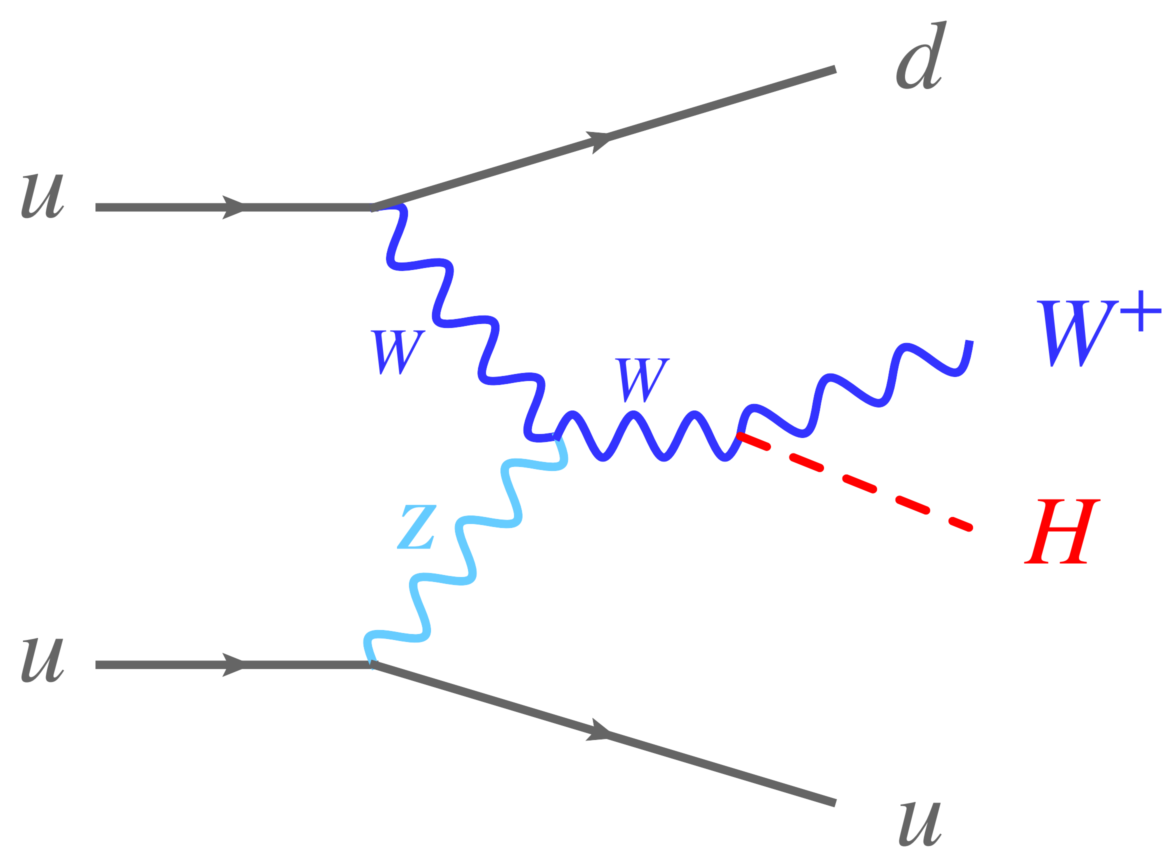


$\sim \kappa_Z^2$

+

Interference

$\sim \kappa_W\,\kappa_Z$



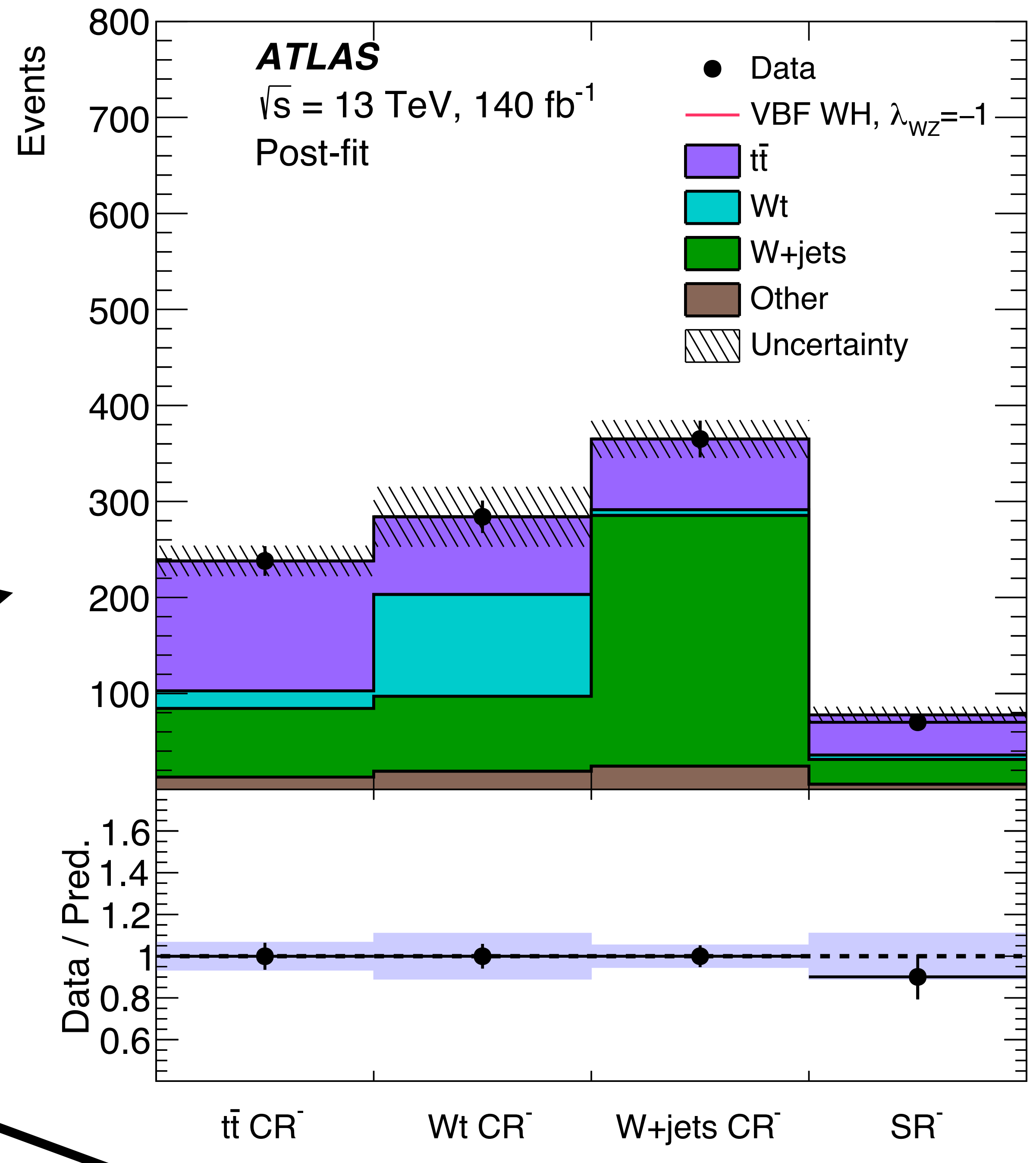
$\sim \kappa_W^2$

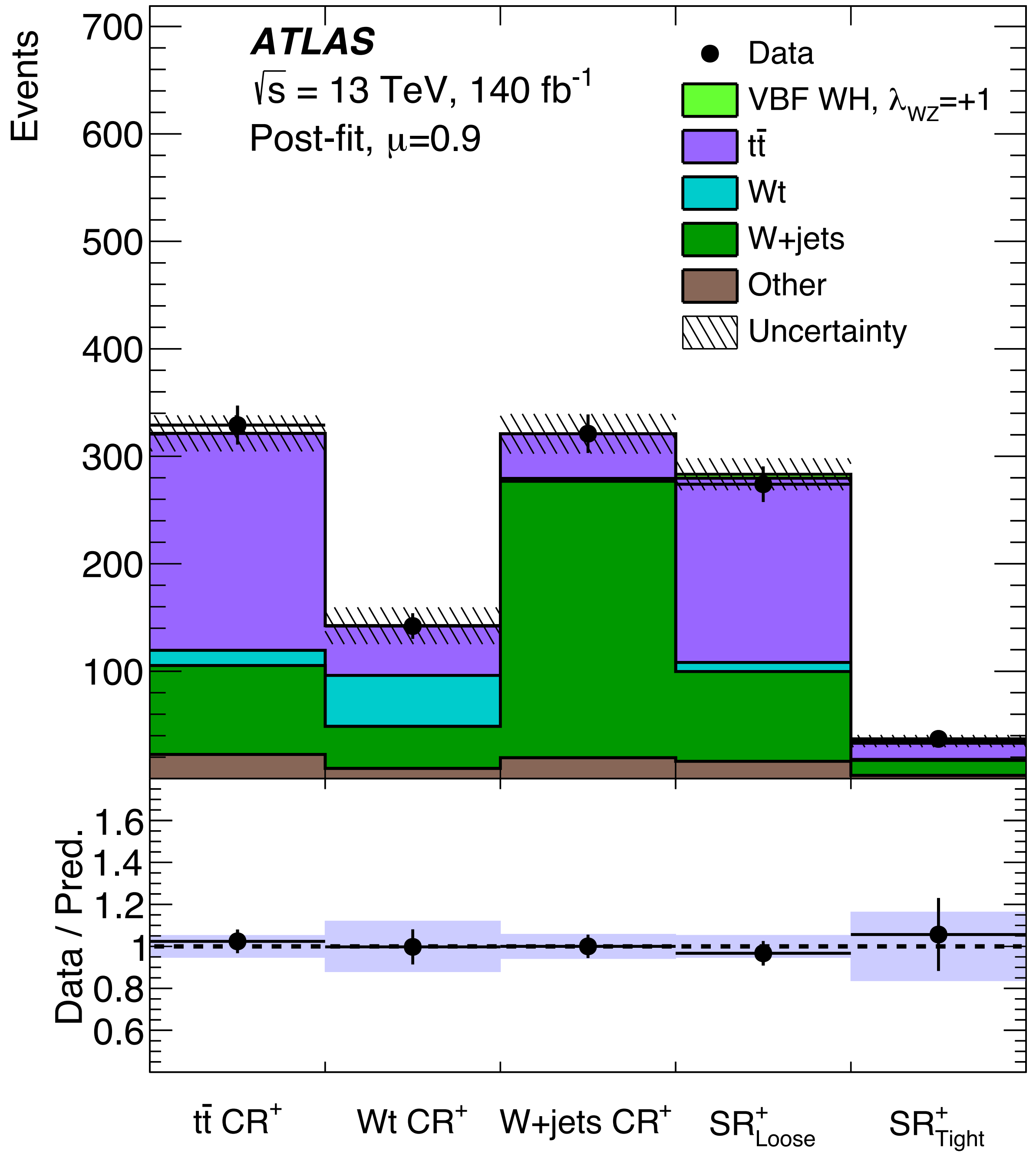
PRL 133.141801

VBF WH(bb)

Analysis in a nutshell

- **Two analyses in parallel:**
  - λ_{WZ} = -1 → Search for BSM scenario
  - λ_{WZ} = 1 → Set limit on SM production
- "Cut-and-count" approach with 2 SRs for positive λ_{WZ} and 1 for negative λ_{WZ}
- Main backgrounds: $t\bar{t}$, W+jets and single top Wt-channel → use dedicated control regions



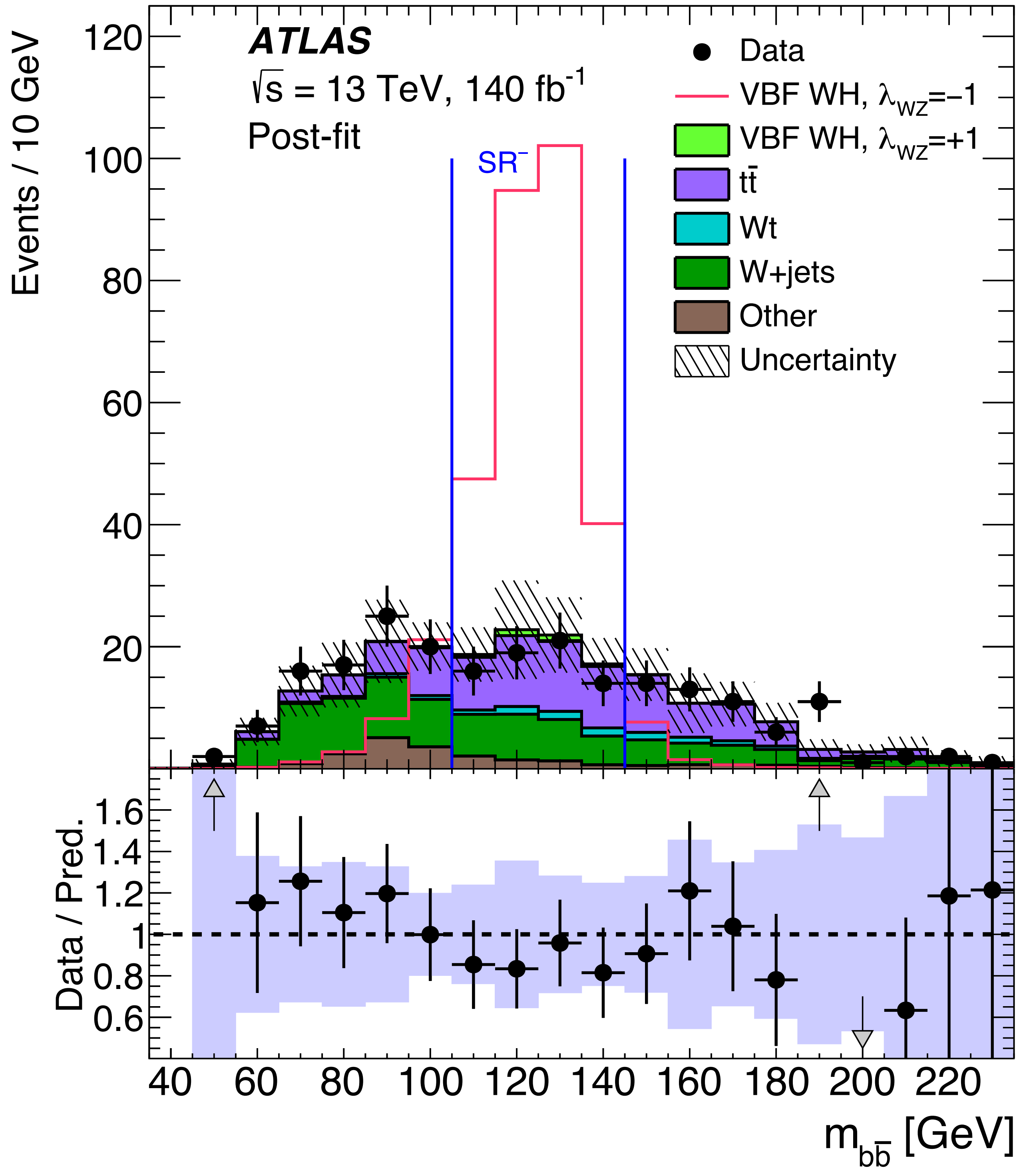


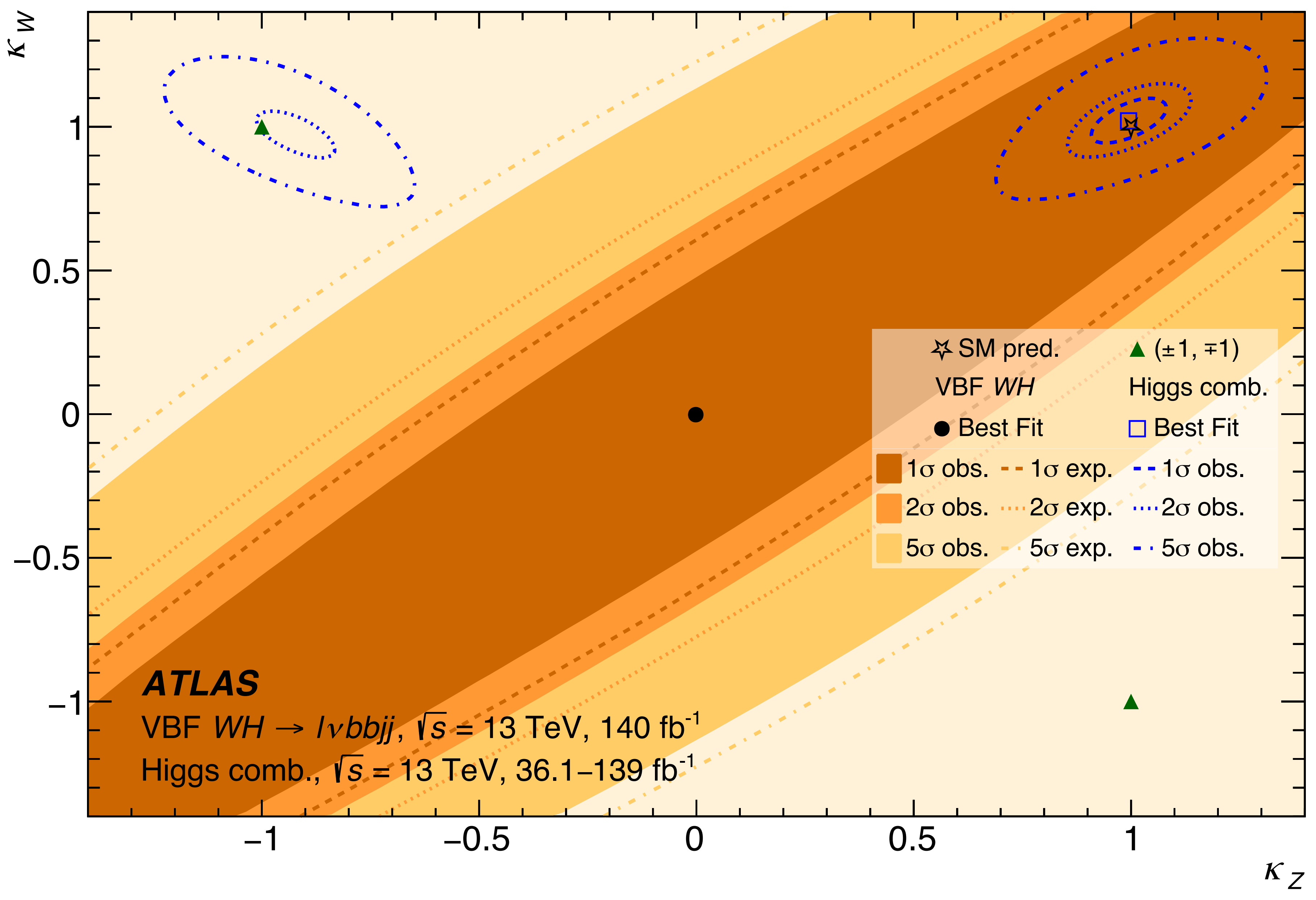
VBF WH(bb)

Results

- **Negative scenario:** $\kappa_W = 1$ and $\kappa_Z = -1$
  - No enhancement was found
- **Positive scenario:** First limit on the obs. (exp.) signal strength: $\mu_{VBF\ WH(bb)} < 9.0\ (8.7) \times SM$
- Exclusion of opposite sign for κ_W and κ_Z with significance >5σ
  - This analysis excludes $\kappa_Z < 0$
  - Previous result from combined Higgs coupling measurement excludes $\kappa_W < 0$

PRL 133.141801



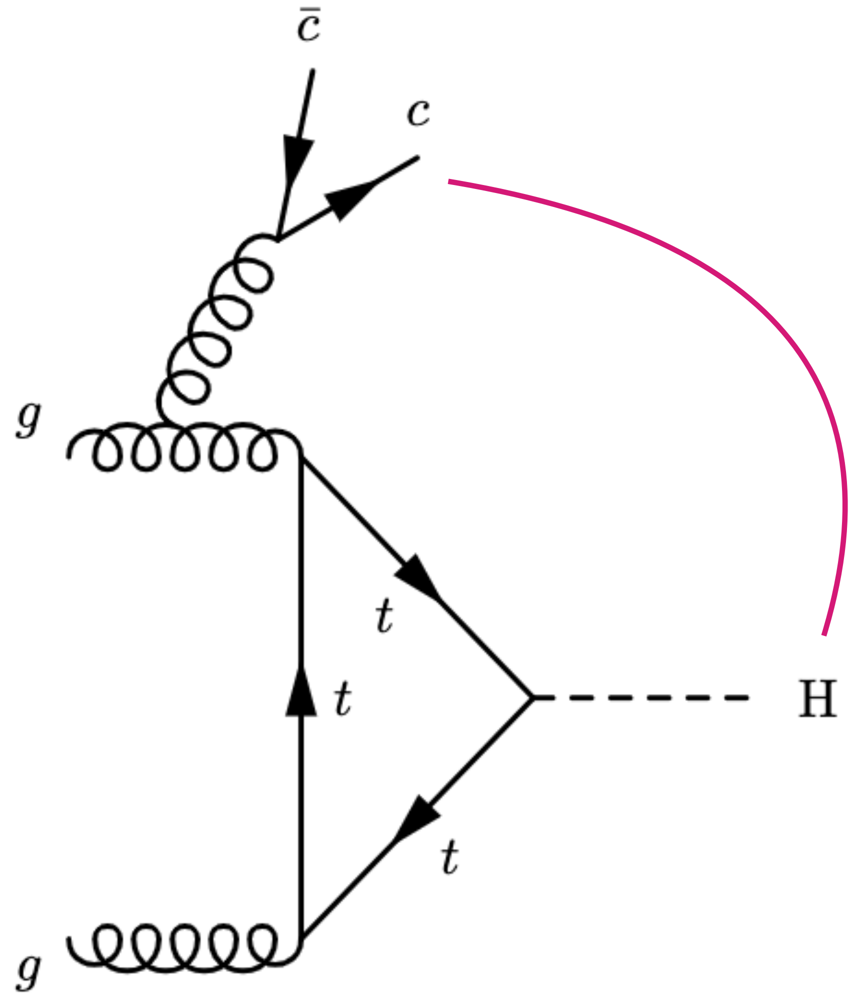


2407.15550

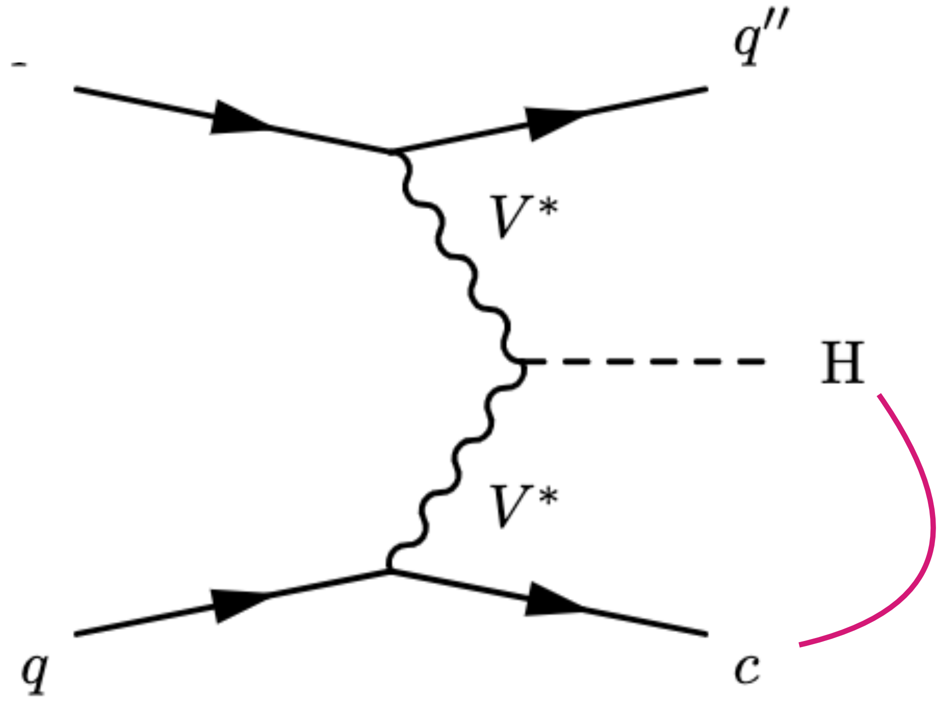
Inclusive H+c

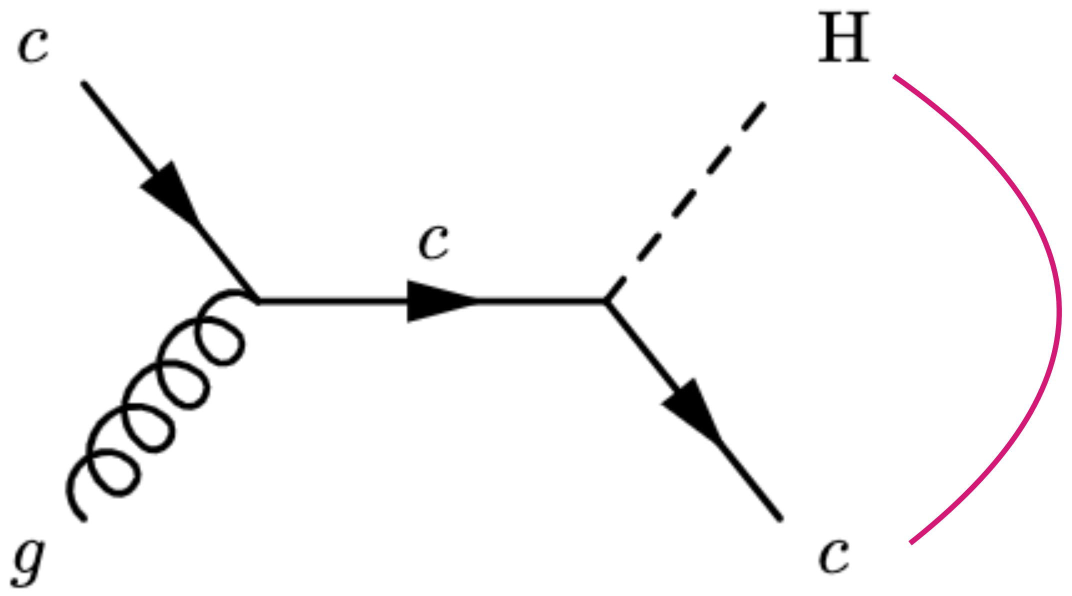
Analysis in a nutshell

- **First inclusive H+c search** using H $\rightarrow \gamma\gamma$:
  - $g + c \rightarrow H + c$ up to two leading order diagram is considered
  - Includes ggF, VBF, VH, ttH and bbH
- **Two categories based on c-tagging:**
  - Leading and/or subleading jets being c-tagged
  - Neither of them being c-tagged
- c-tagging: $\epsilon_c \approx 40\,\%$, $\epsilon_b \approx 20\,\%$, $\epsilon_l \approx 5\,\%$



Requires
$\Delta R(\gamma_{1,2}, c) > 1$





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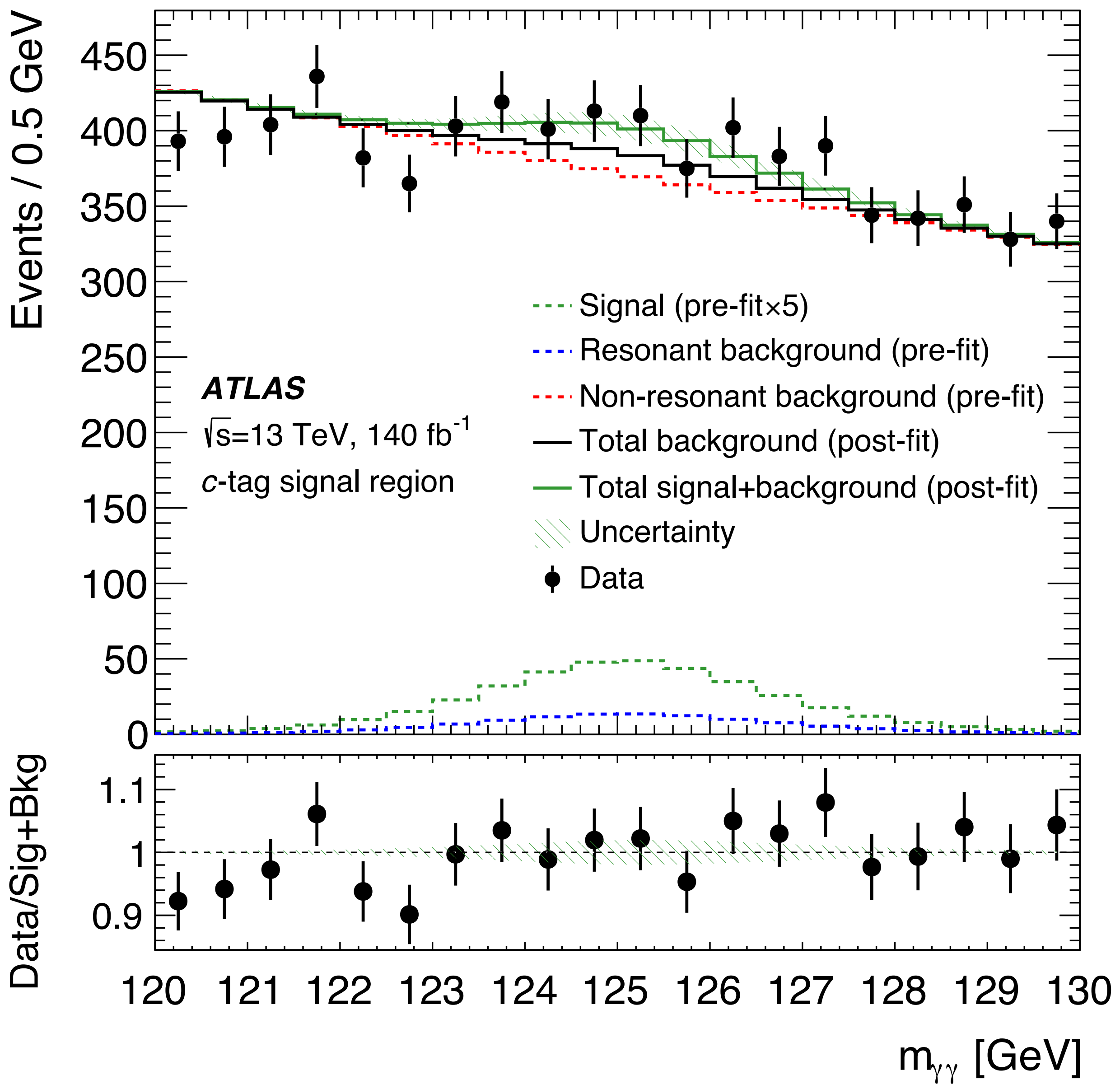
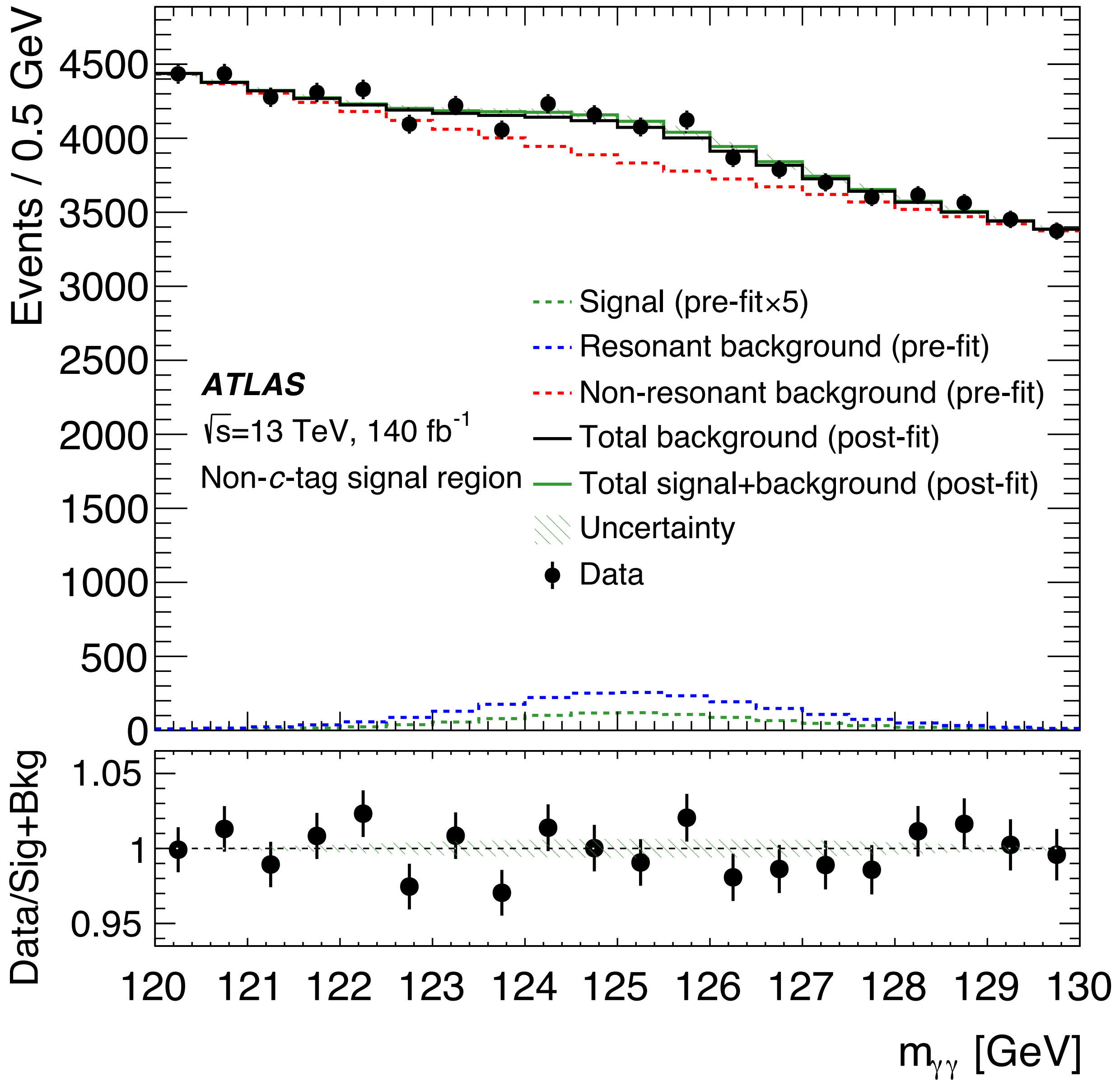
Inclusive H+c

Results

- Binned profile likelihood fit to $m_{\gamma\gamma}$ observable:
- Obs. (exp.) best fit value for the cross-section: 5.3±3.0 (2.9±2.8) pb
    - With a significance of 1.7 (1.0) σ
- **Set an upper limit on the inclusive H+c cross-section:**

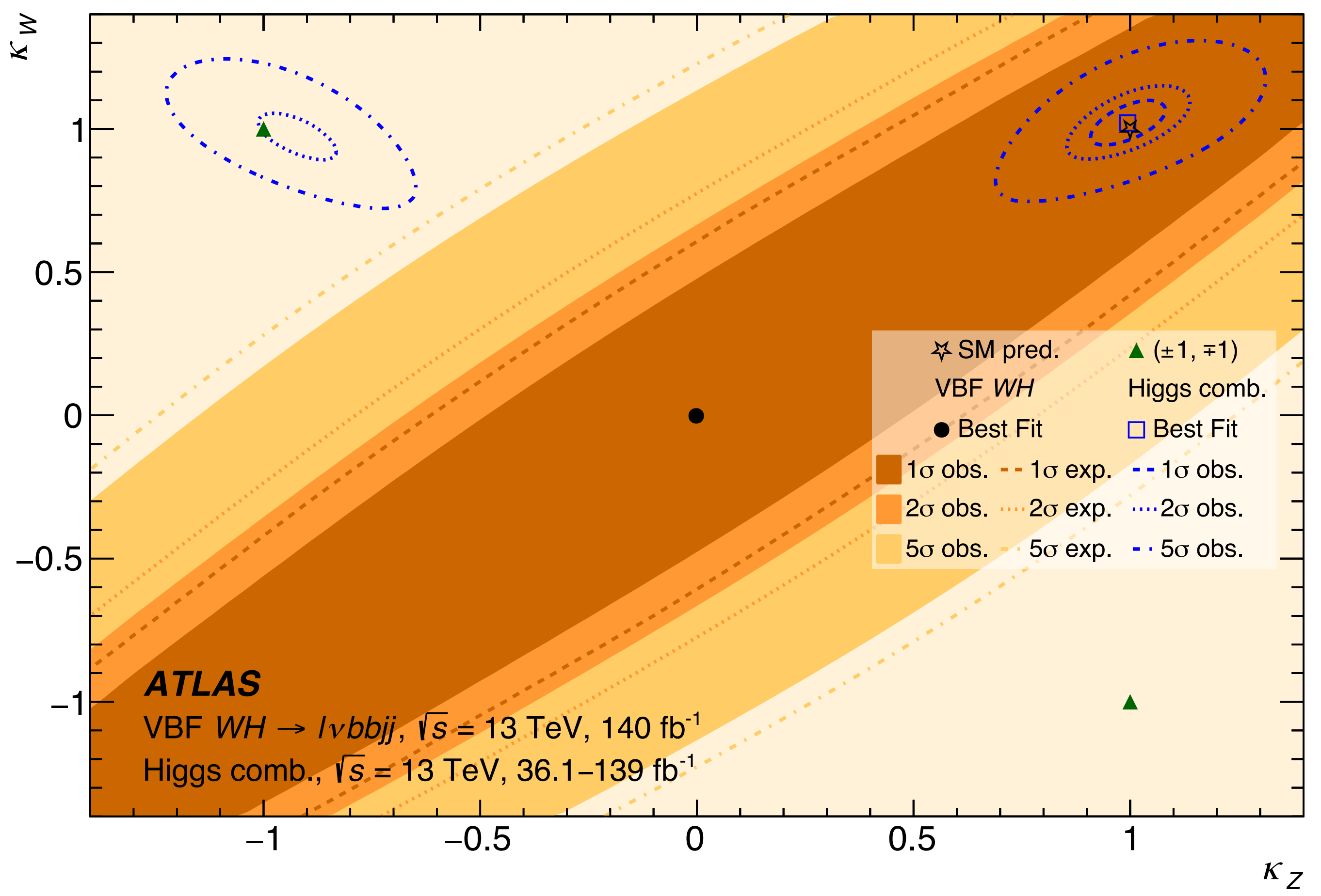
Category	c-tagged	Non c-tagged	Combined
Obs. (exp) limit at 95% CL [pb]	15 (9.6)	11 (14)	10.4 (8.6)

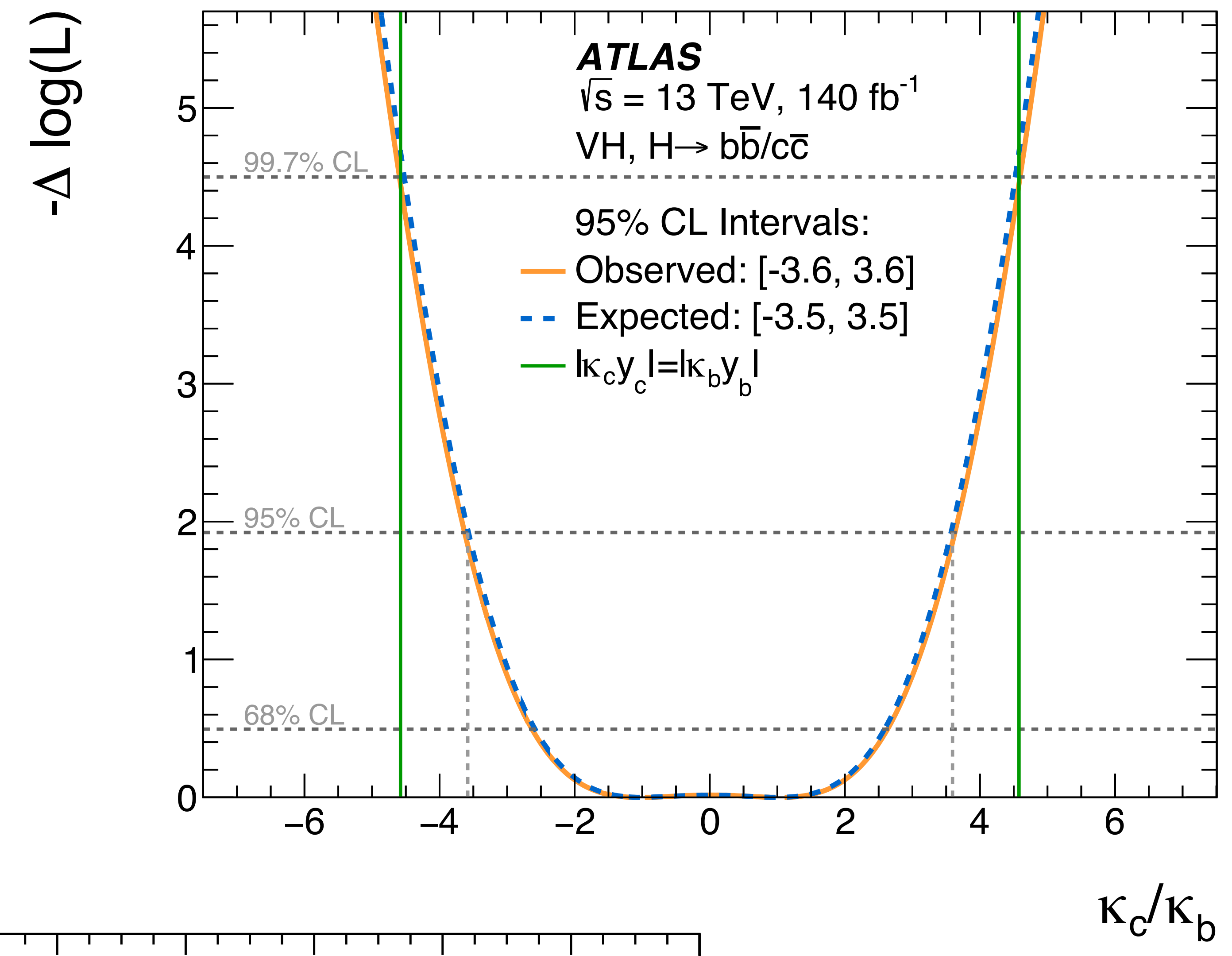


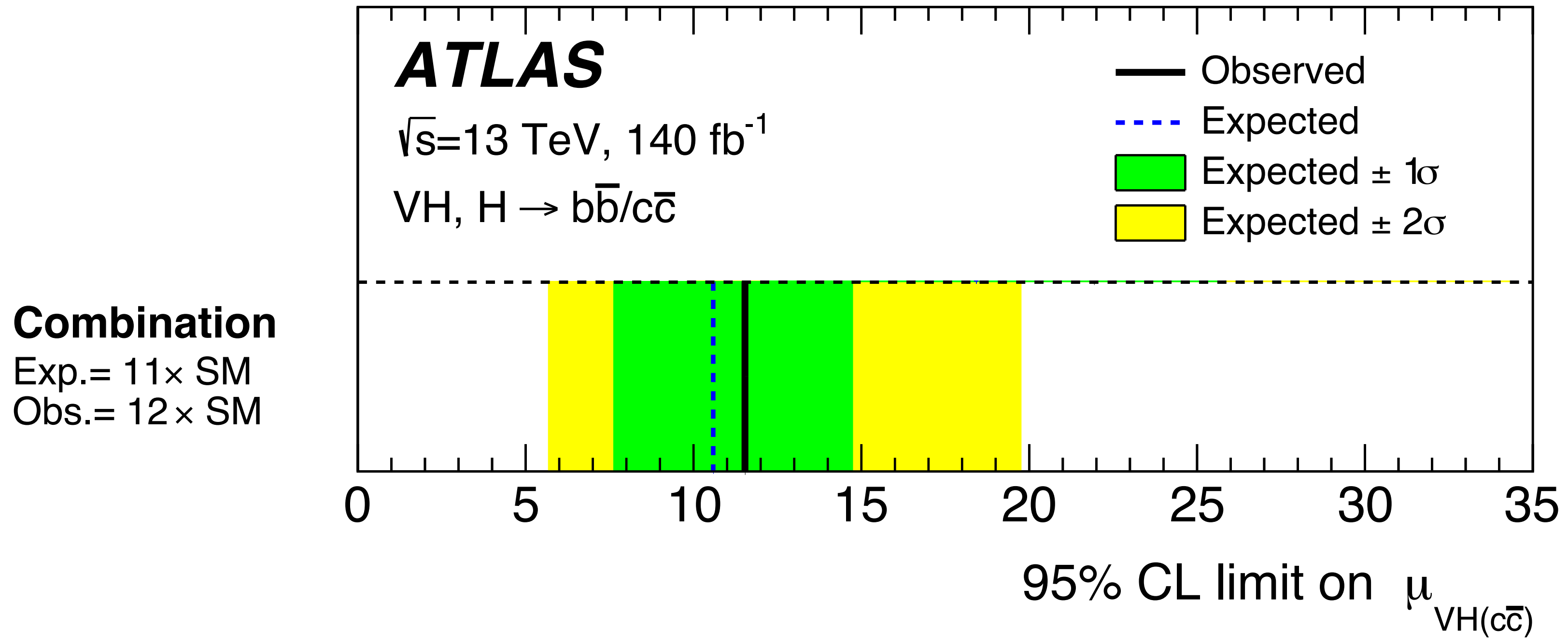


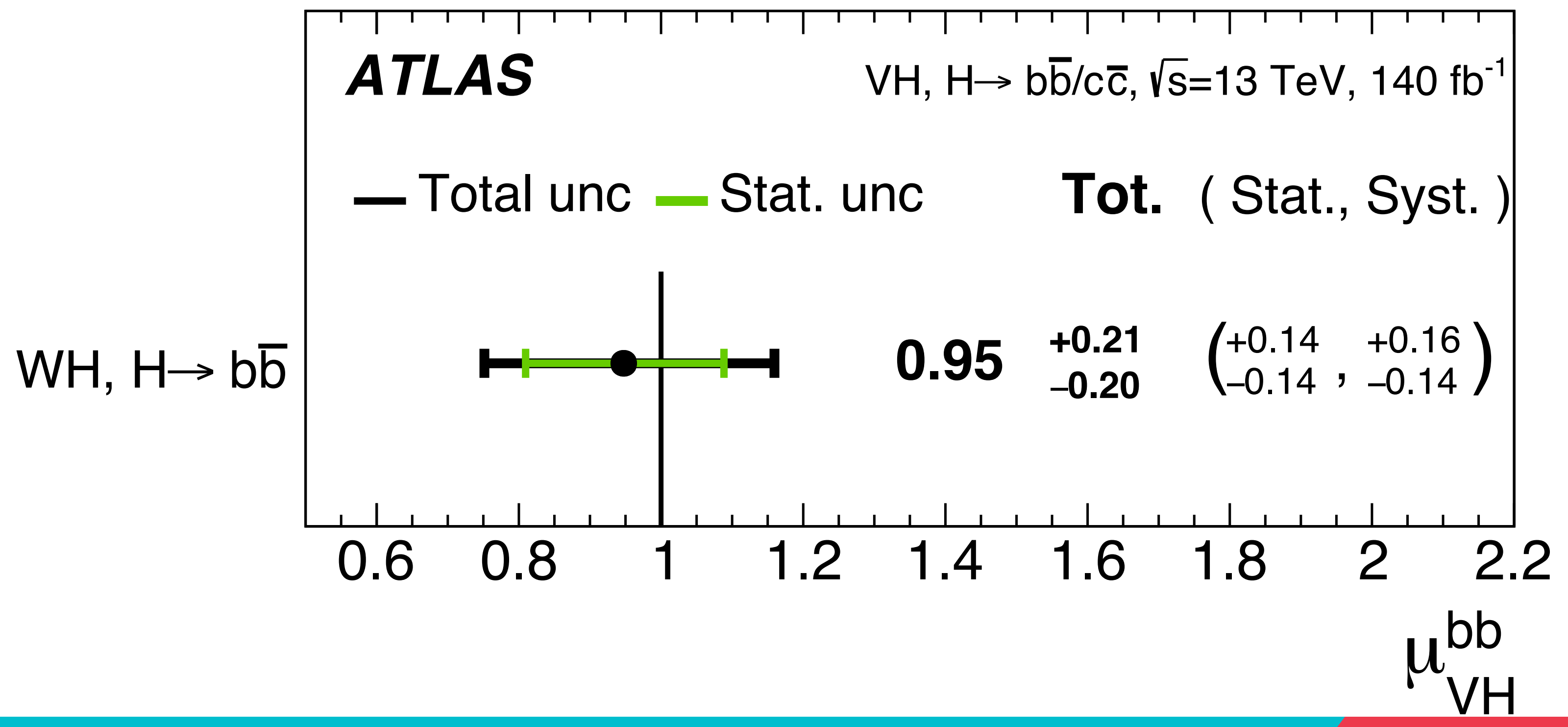
Conclusion

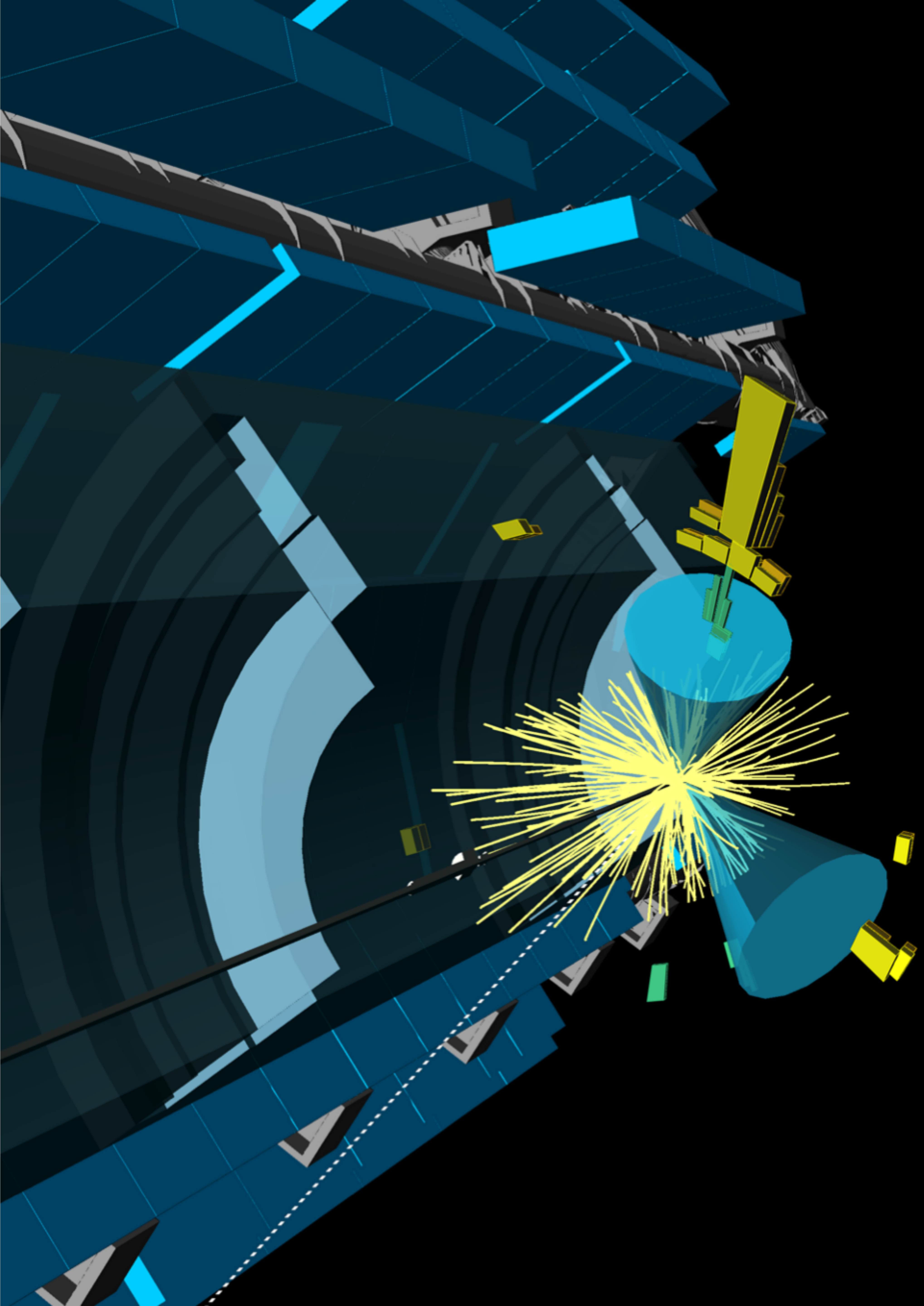
- Using decays in b- and c-quarks is crucial to probe Higgs boson coupling properties:
  - Higgs couplings to W and Z bosons have the same sign
  - Higgs coupling to charm is weaker than to beauty
  - First observation of WZ(bb) and WH(bb)
- But also set upper limit on rare processes:
  - With the most precise limit on VH(cc): $\mu < 11.5 \times SM$











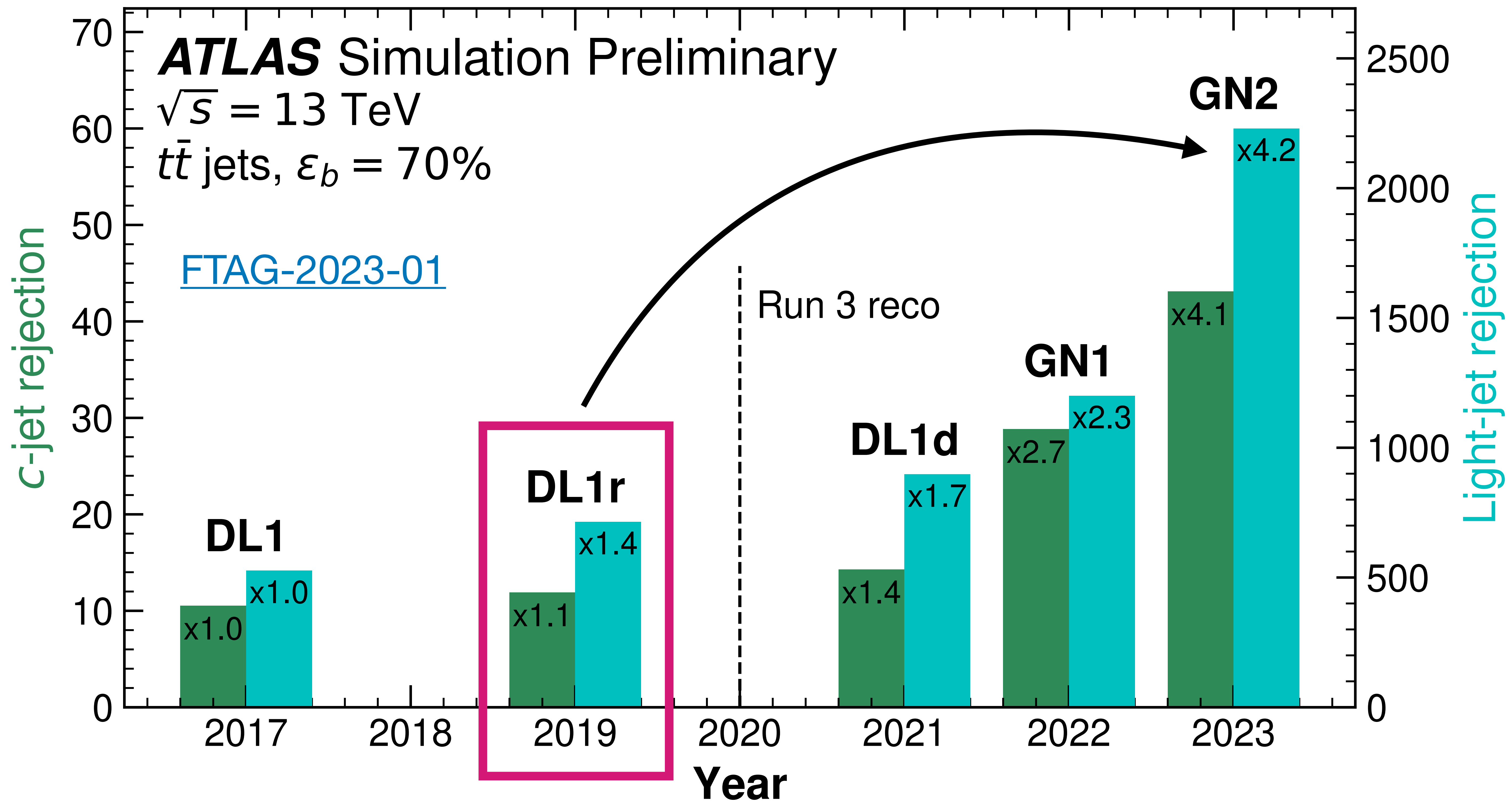
Thank you
for
your attention

VH(bb/cc)

Flavour tagging

Large improvement for future analyses

c- and light-jet rejection with different taggers at 70% $t\bar{t}$ WP



Tagger used in the VH(bb/cc) analysis

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VH(bb/cc)

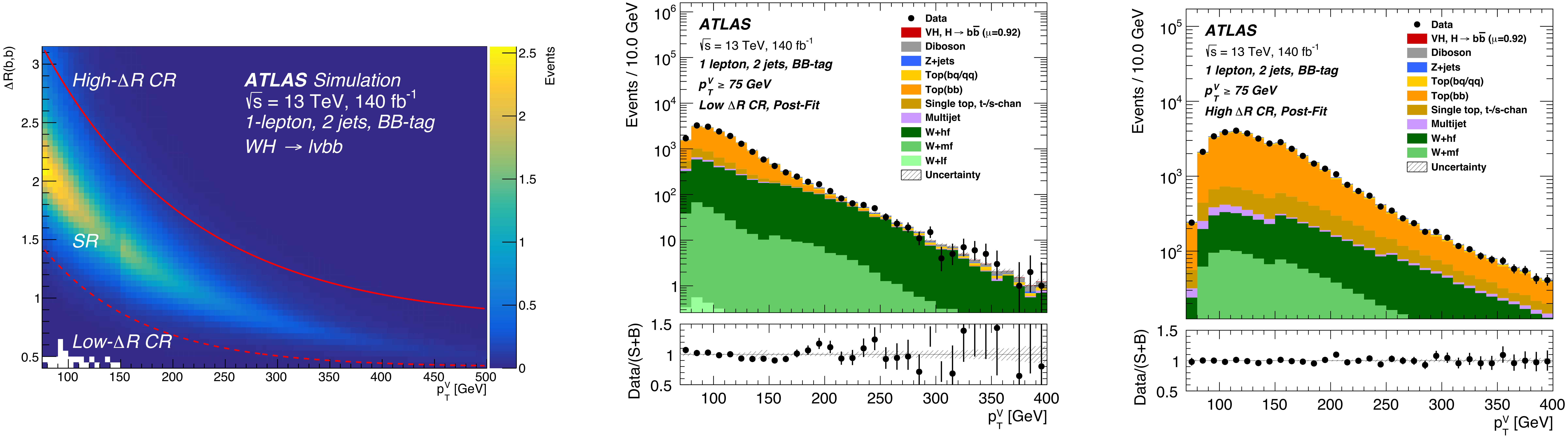
BDT inputs

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

Nikhef

VH(bb/cc)

ΔR control region



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VH(bb/cc)

Control regions & fit variables

Channel	Region	BB	C_TN	C_TC_L	C_TC_T	BC_T	C_LN
0-lepton	High-ΔR CR	Norm. Only *				—	
	BC_T Top CR	—				$m_{j_1 j_2}$	—
	$V+lf$ CR	—					Norm. Only *
1-lepton	Low-ΔR CR	$\text{BDT}_{\text{Low-}\Delta R\ \text{CR}}$	—				
	High-ΔR CR	p_T^V		$m_{j_1 j_2}$		—	
	BC_T Top 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 $e\mu$ CR	—	Norm. Only *			–	—
	$V+lf$ CR	—					p_T^V

* Only event yield is used in the fit

VH(bb/cc)

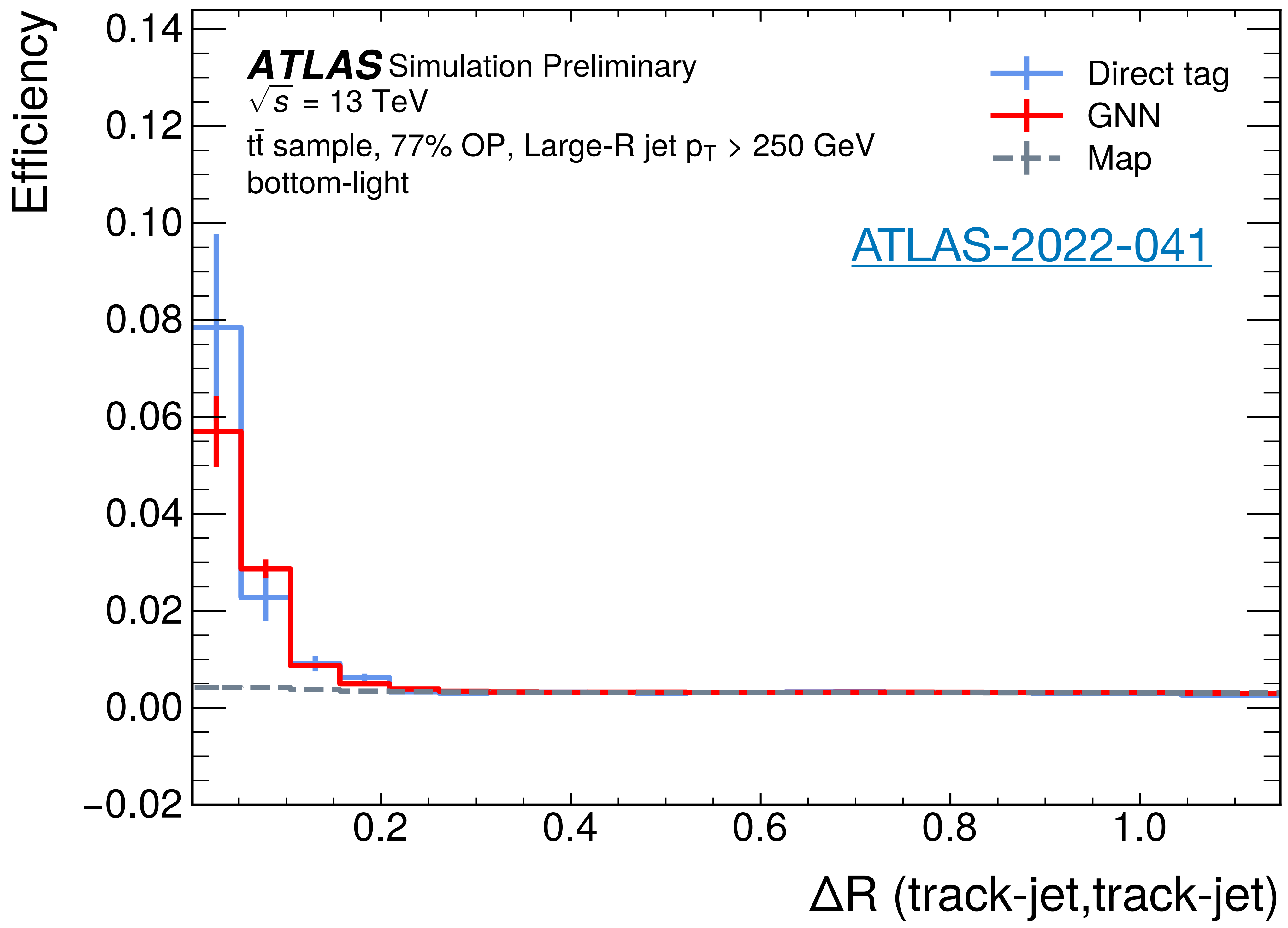
Truth tagging

- Lack of MC statistics to well model the backgrounds because of the tagging strategy that suppress background dominated events

- Solution: truth tagging → reweight events based on the probability to pass tagging requirements

  - Use of GNN which considers kinematic properties and correlations between jets

  - Large reduction of mismodelling and good closure within statistical uncertainties



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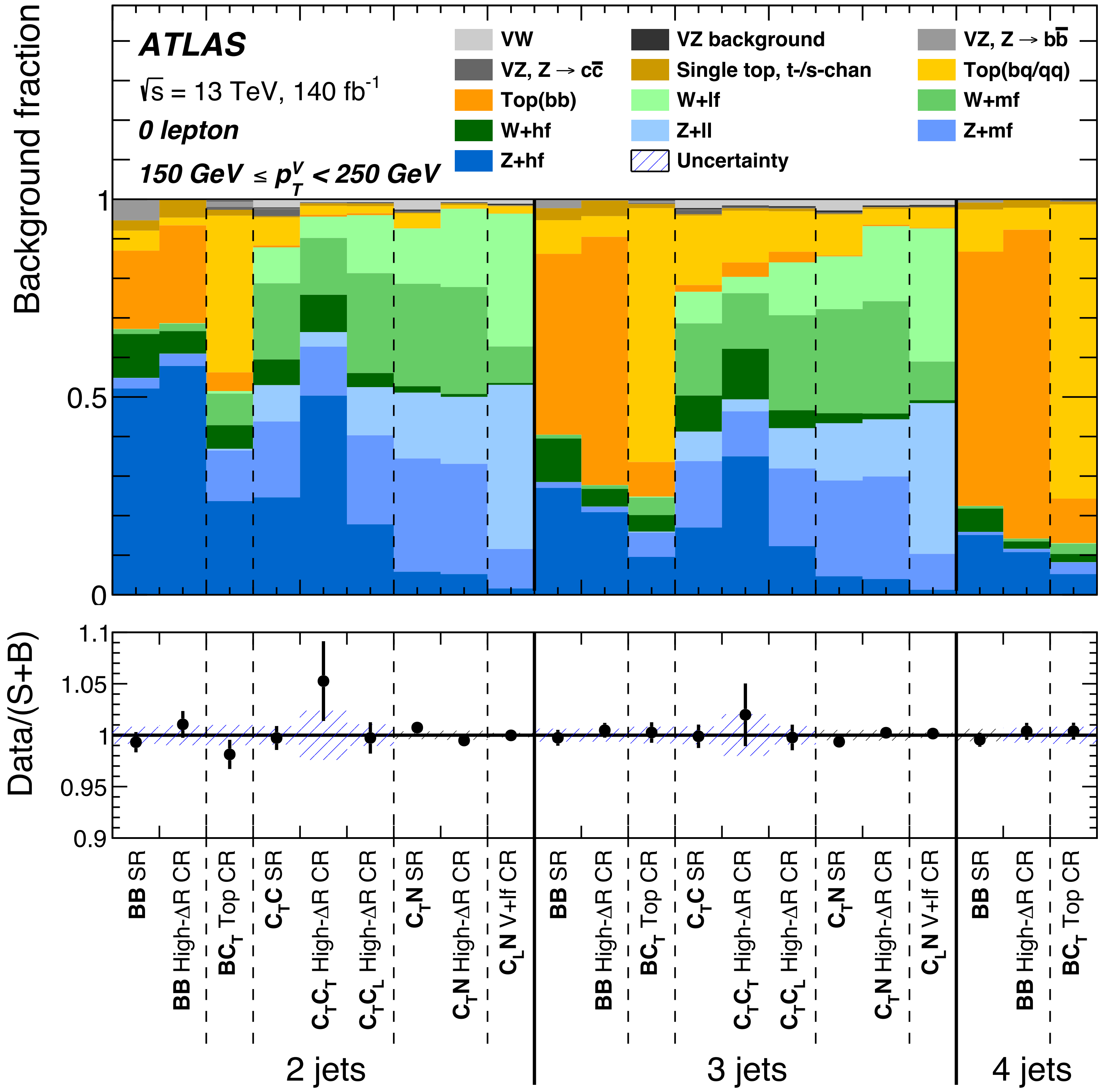
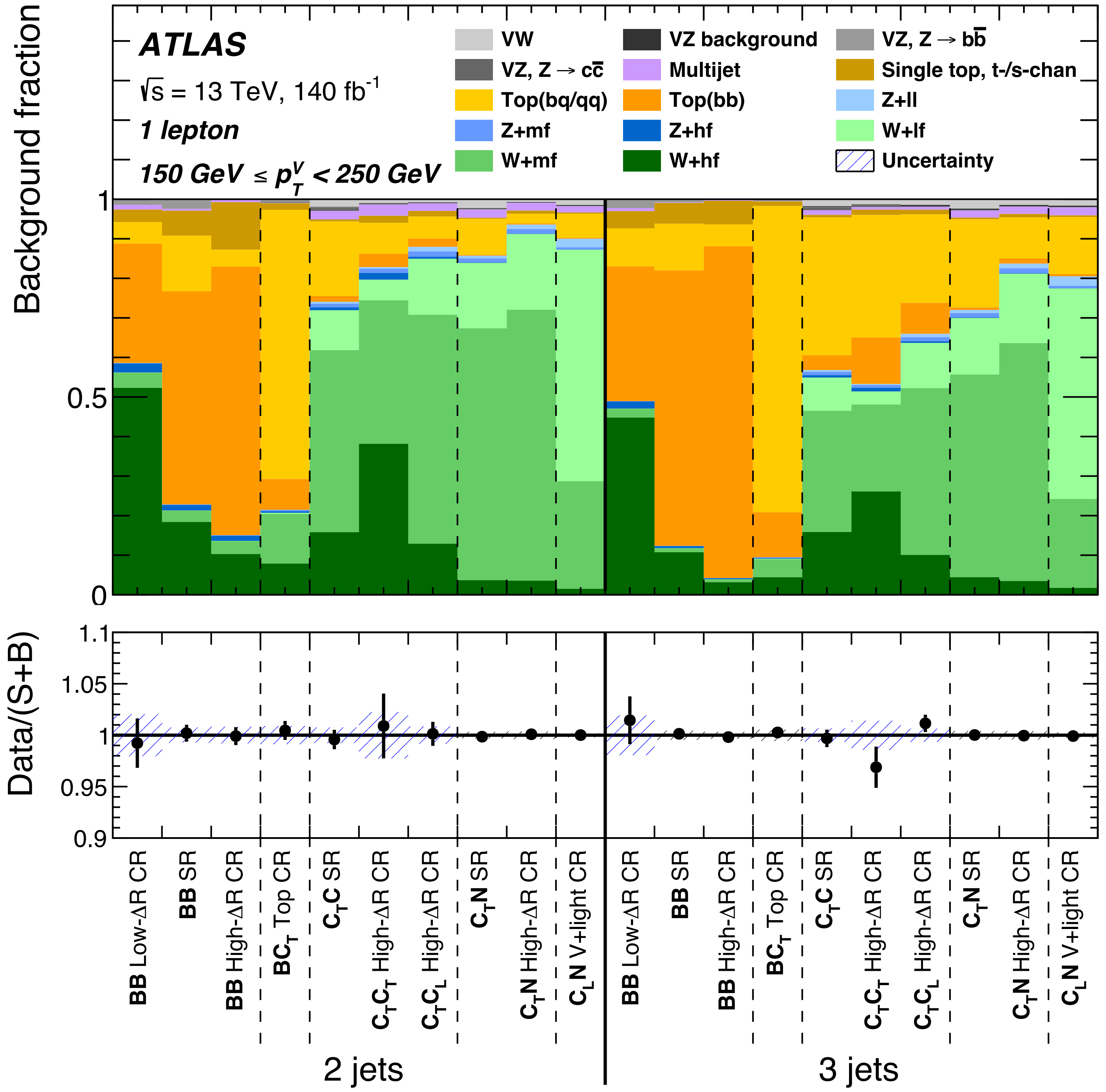
VH(bb/cc)

Background composition

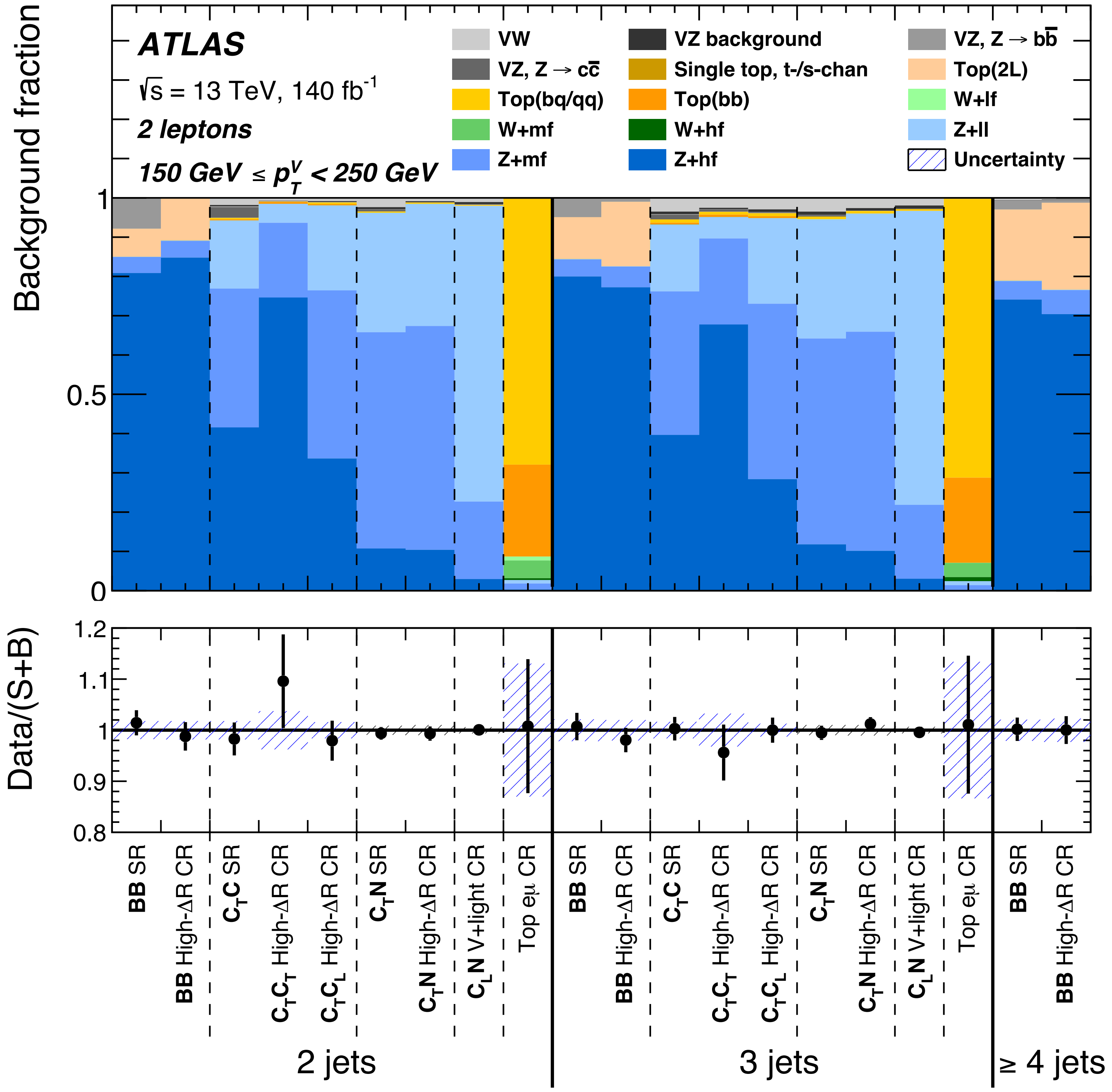
0-lepton channel



1-lepton channel



2-lepton channel

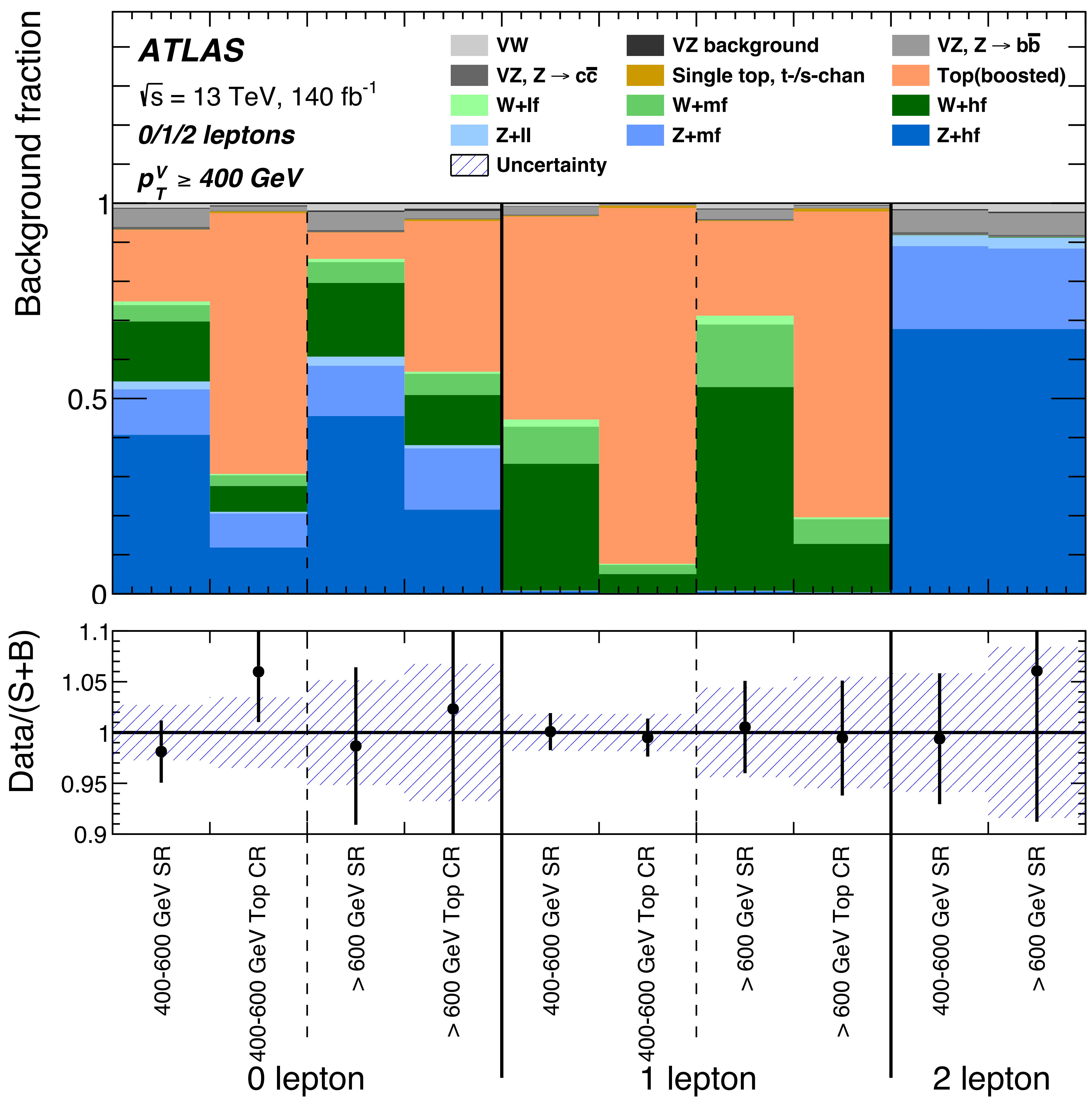


Nikhef

VH(bb/cc)

Background composition

Boosted VH(bb)



[2410.19611](2410.19611)

VH(bb/cc)

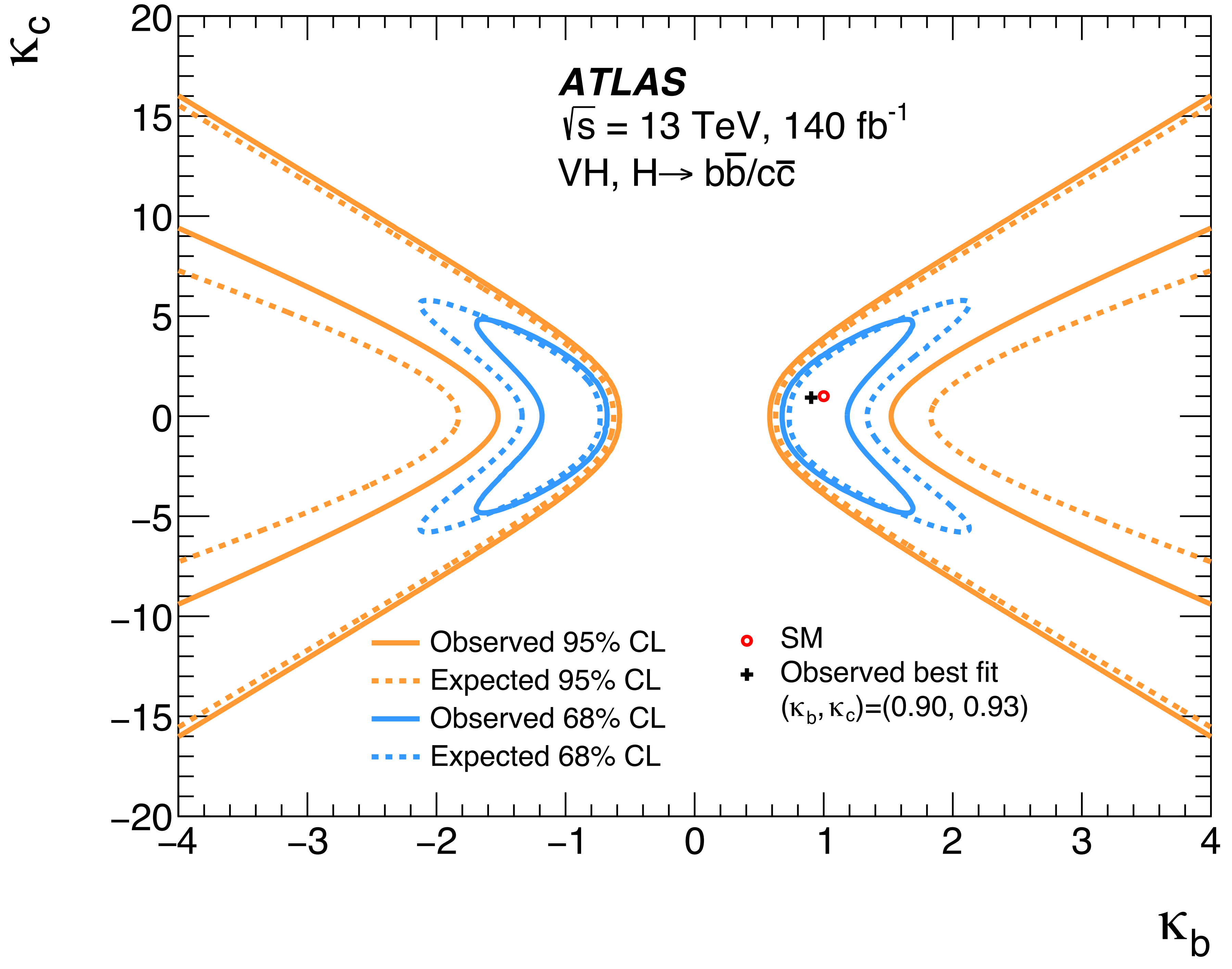
Results: Breakdown table

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_T^{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

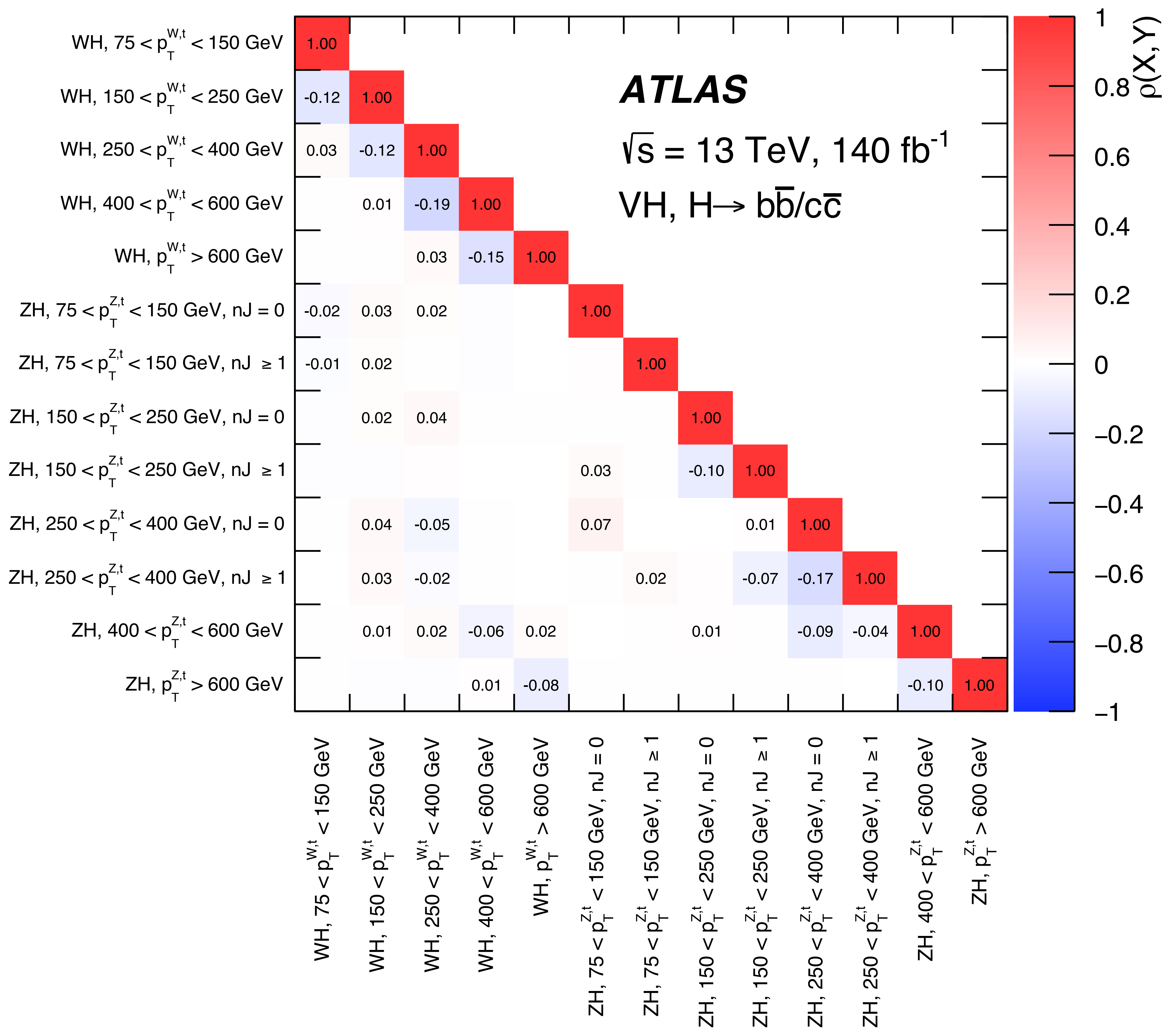
VH(bb/cc)

Results

Higgs coupling: 2D scan



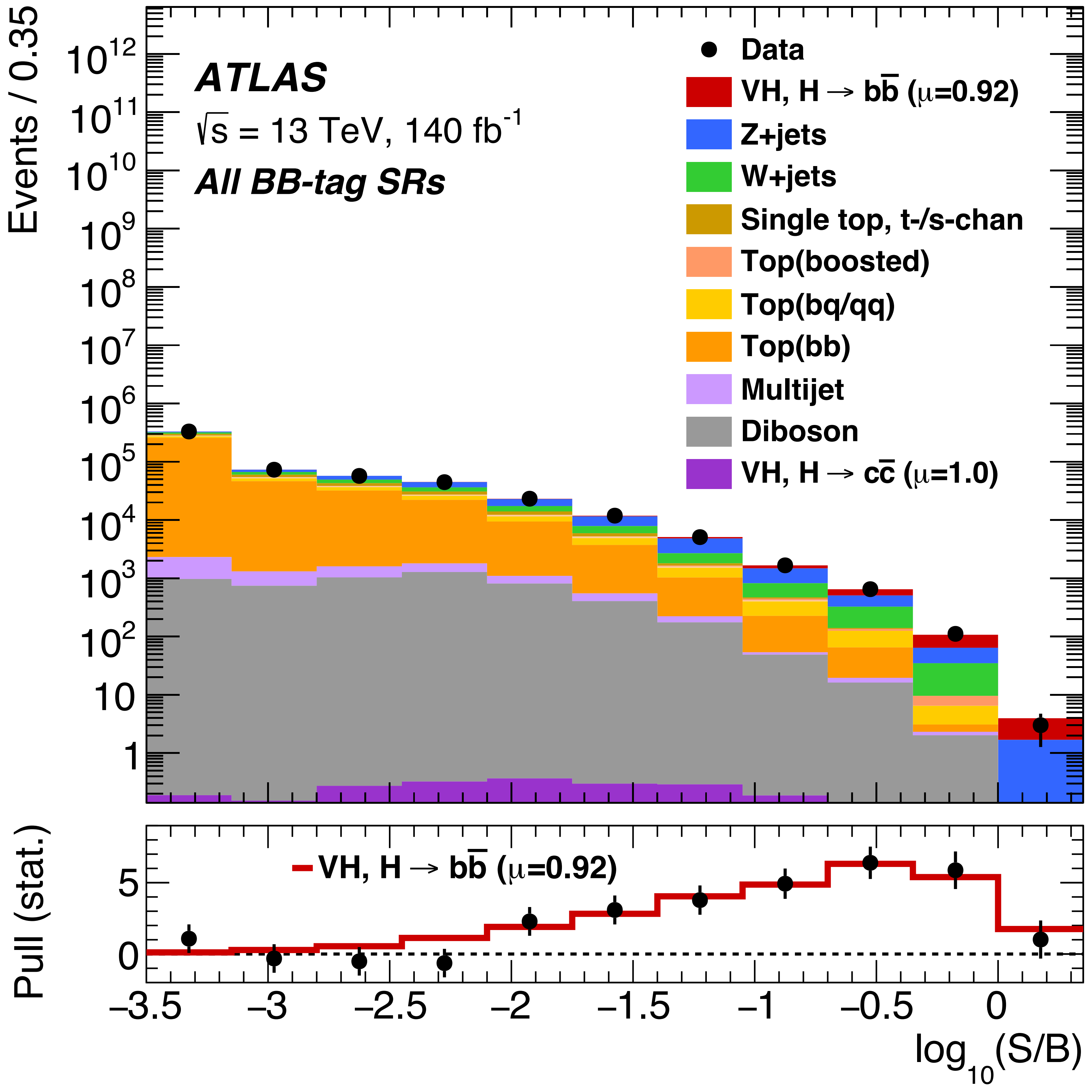
STXS measurement: correlation matrix



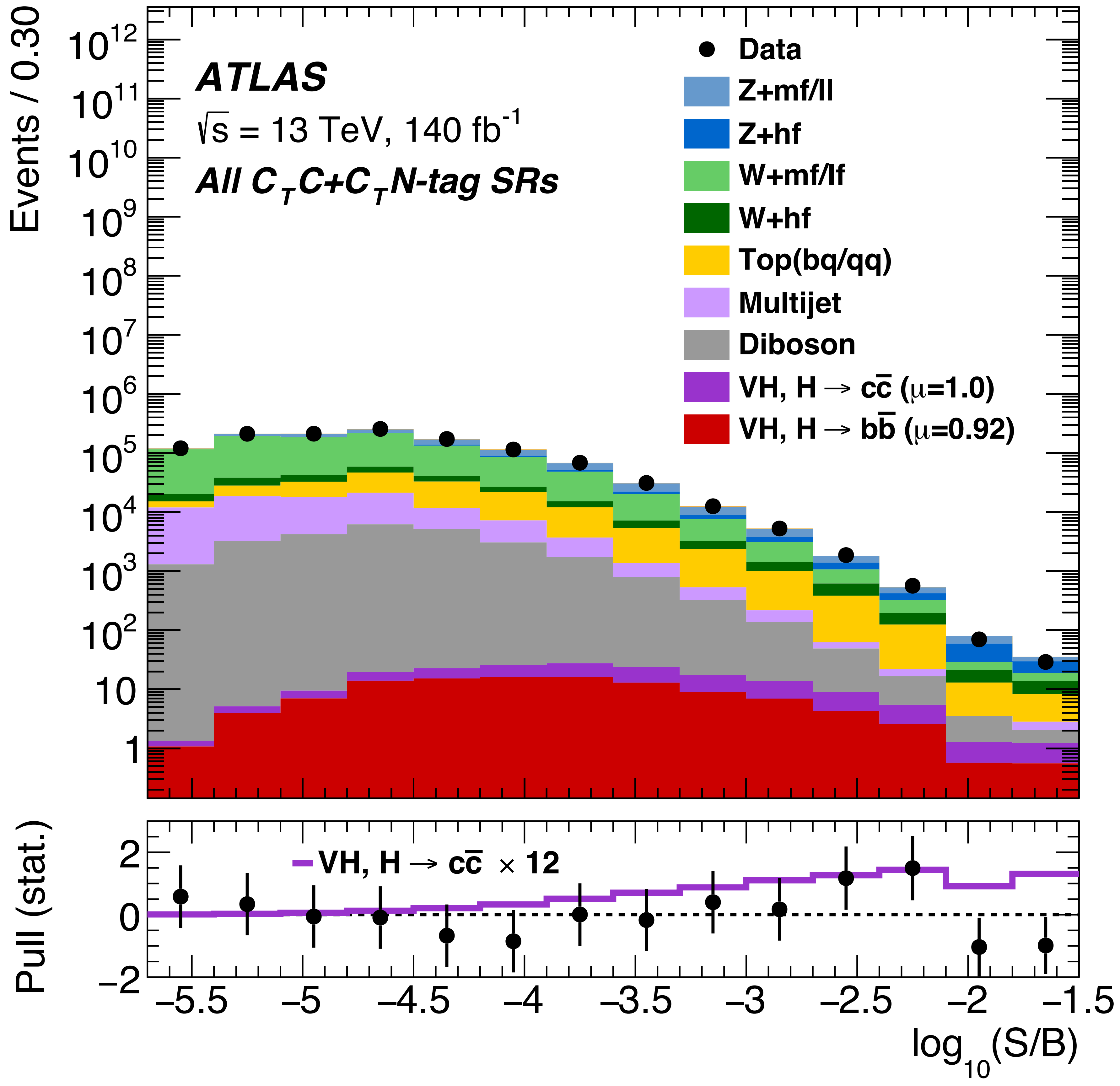
VH(bb/cc)

Results

VH(bb)



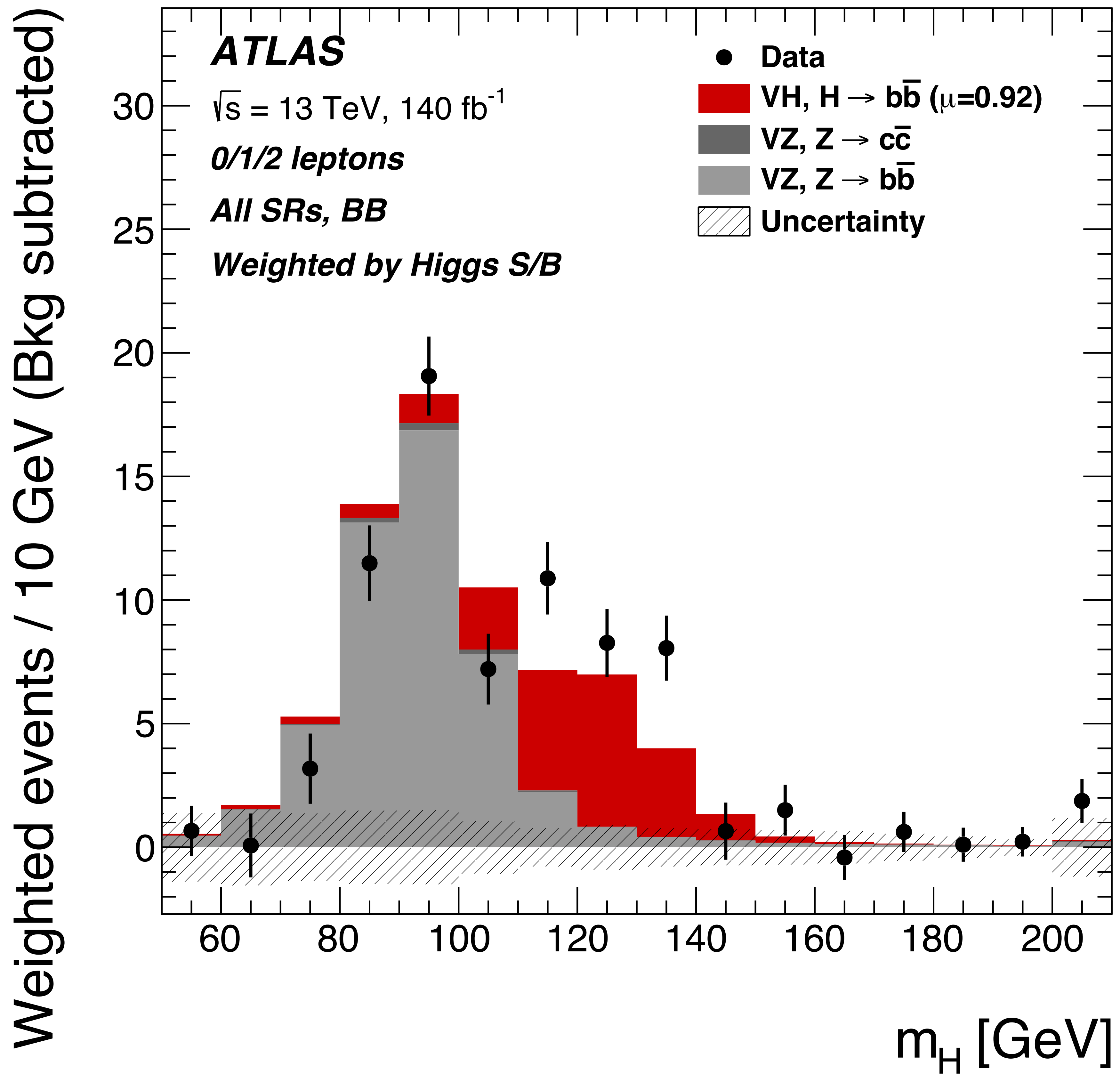
VH(cc)



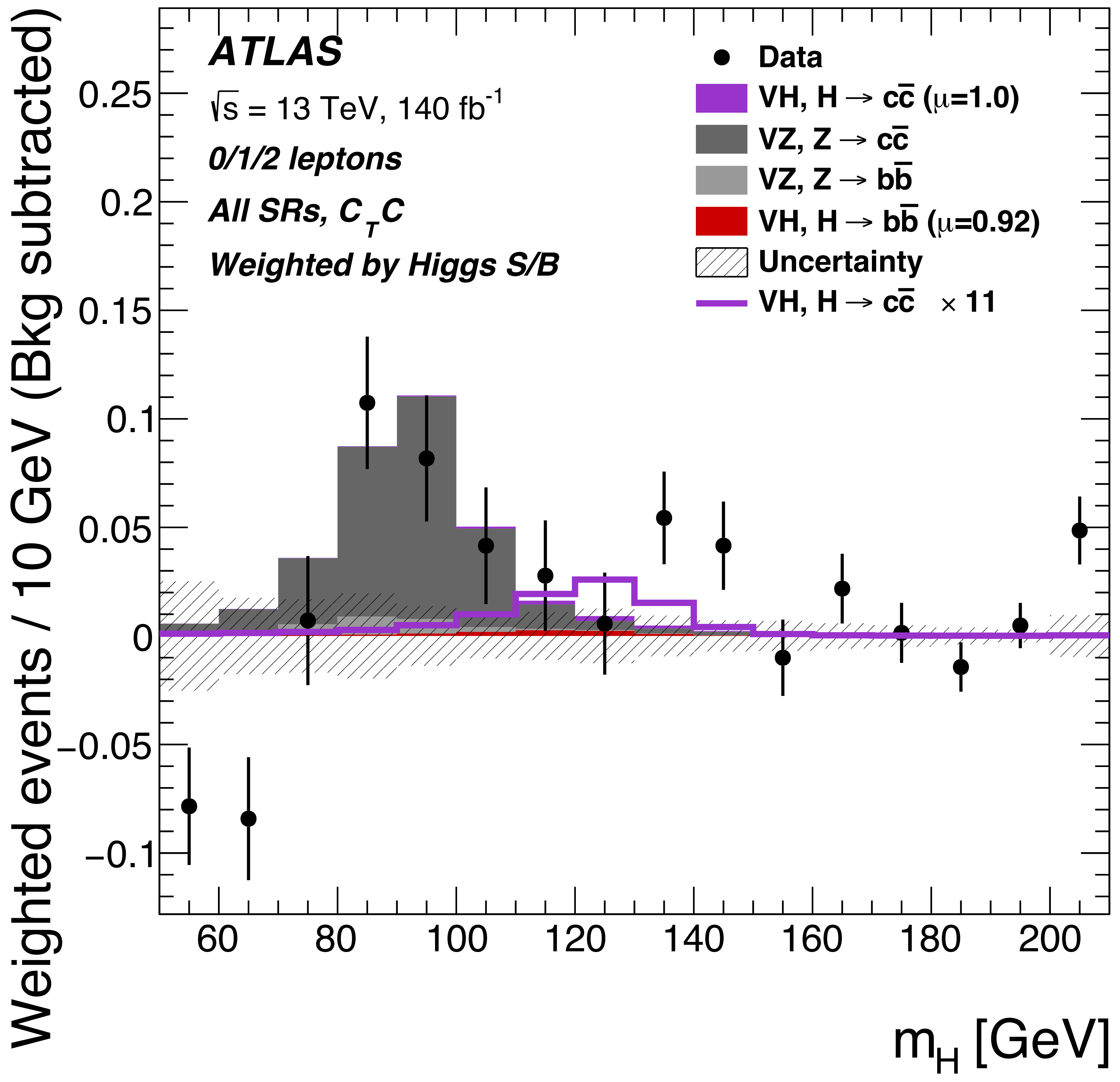
VH(bb/cc)

Results

VH(bb)



VH(cc)



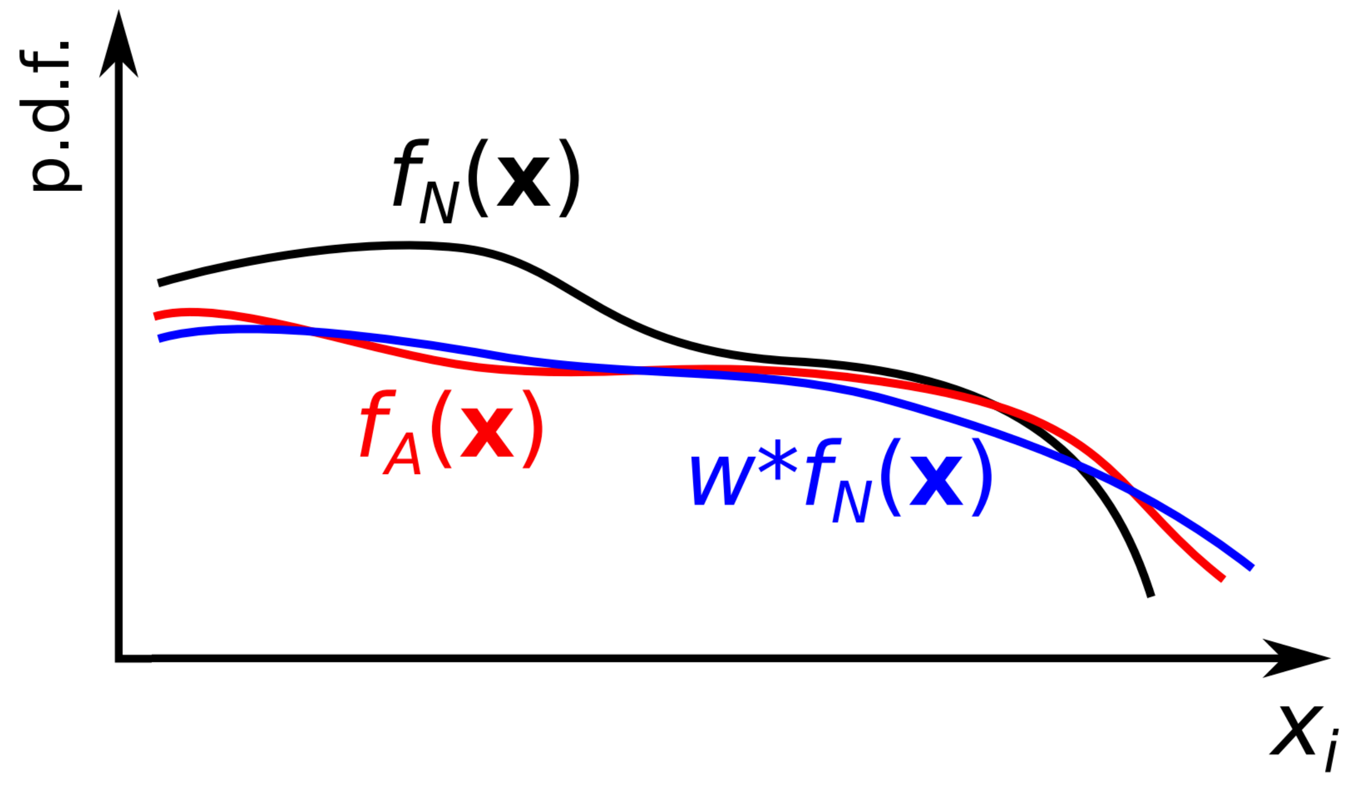
Nikhef

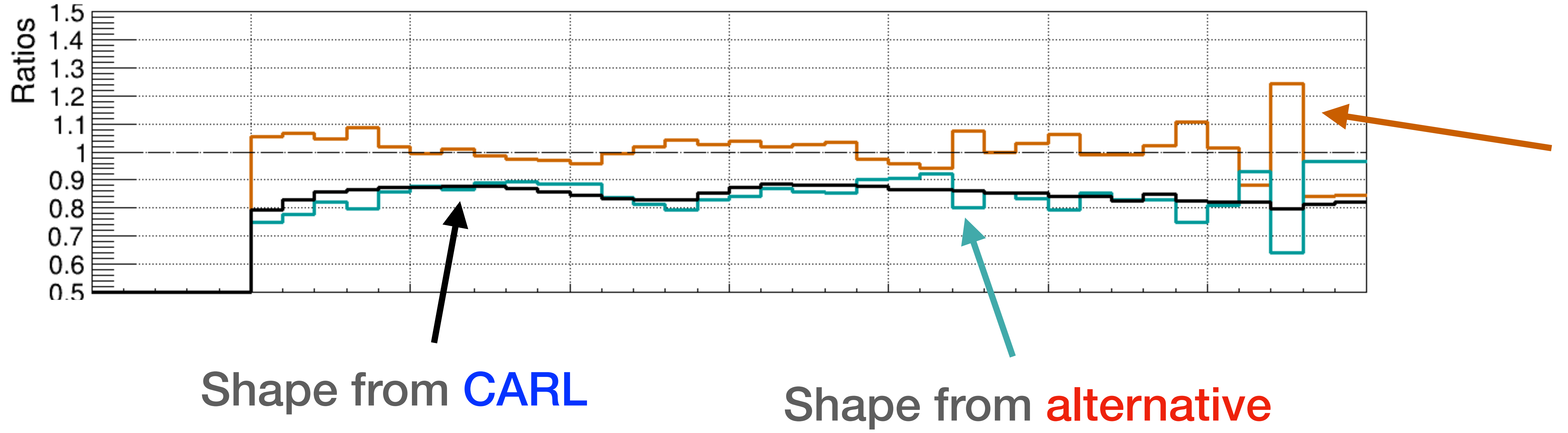
VH(bb/cc)

Increased statistics for alternative samples

- Some alternative samples have limited statistics → use CARL (Calibrated Likelihood Ratio Estimator)
  - Deep neural network which reweight the **nominal** sample so it will match the alternative sample
  - Can benefit from large statistics of the nominal sample and a smoother distribution

Comparison between **Nominal**, **Alternative** and **Reweighted** samples





Difference between the alternative and reweighted samples

PRL 133.141801

VBF WH(bb)

Signal regions

Variable	Description	SR^-	SR^+_{loose}	SR^+_{tight}
$m_{b\bar{b}}$	Invariant mass of the two b-jets ($b\bar{b}$ system).	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV
$\Delta R_{b\bar{b}}$	ΔR between the two b-jets.	< 1.2	< 1.6	< 1.2
$p_T^{b\bar{b}}$	p_T of the $b\bar{b}$ system.	> 250 GeV	> 100 GeV	> 180 GeV
m_{jj}	Invariant mass of the VBF jets.	–	> 600 GeV	> 1000 GeV
Δy_{jj}	Rapidity separation of the VBF jets.	> 4.4	> 3.0	> 3.0
m_{top}^{lep}	Invariant mass of the W and either b-jet that is closest to 172.7 GeV (m_{top}).	> 260 GeV	> 260 GeV	> 260 GeV
$\xi_{Wb\bar{b}}$	$\frac{\lvert y_{Wb\bar{b}} - y_{jj} \rvert}{\Delta y_{jj}}$, where $y_{Wb\bar{b}}$ (y_{jj}) is the rapidity of the $Wb\bar{b}$ (VBF-jet) system.	< 0.3	< 0.3	< 0.3
$\Delta\phi(Wb\bar{b}, jj)$	Azimuthal separation between the $Wb\bar{b}$ system and the VBF-jet system.	–	–	> 2.7
N_{jets}^{veto}	Number of nontagged, non-VBF jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.5$.	–	≤ 1	$= 0$

VBF WH(bb)

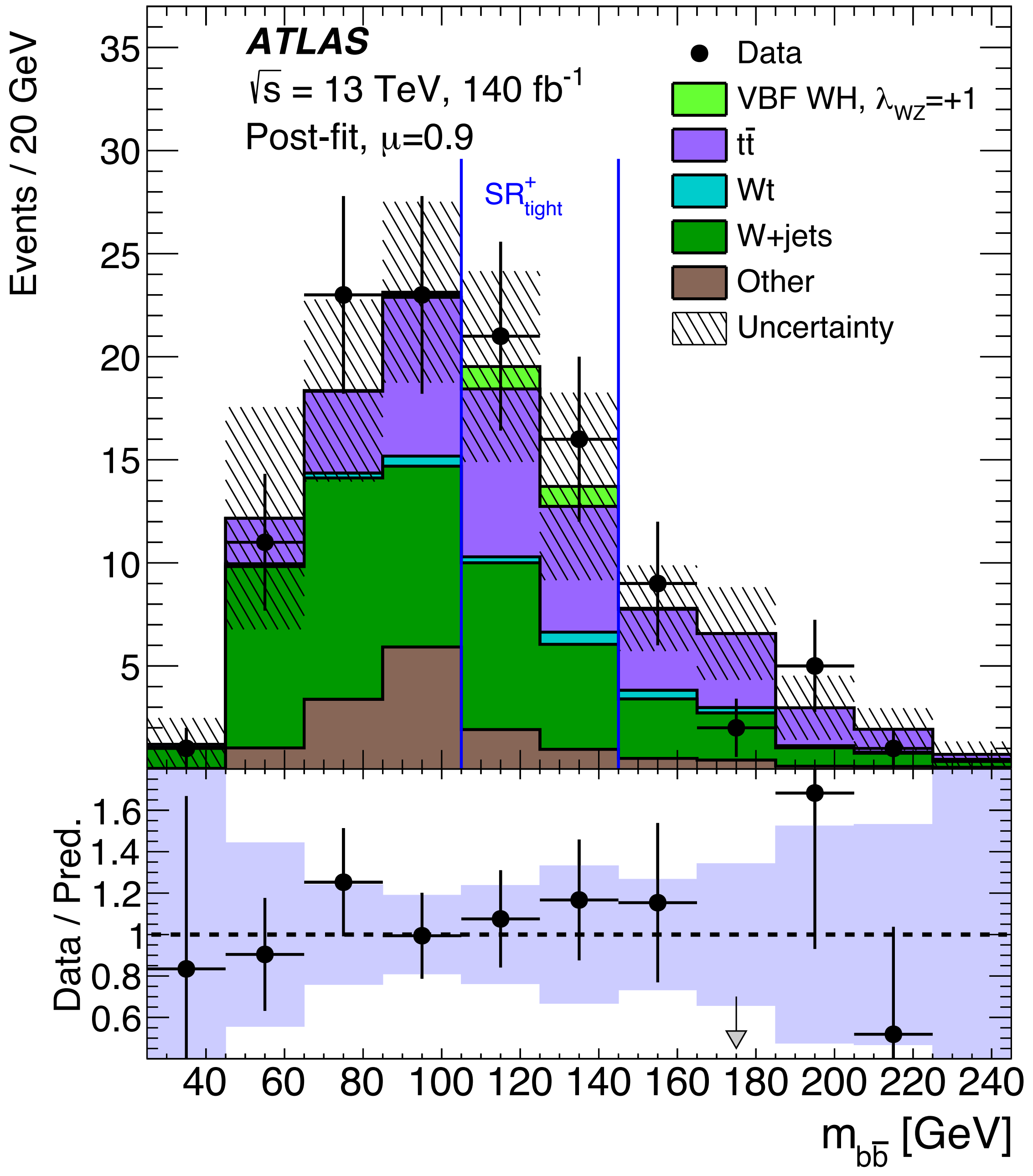
Control regions

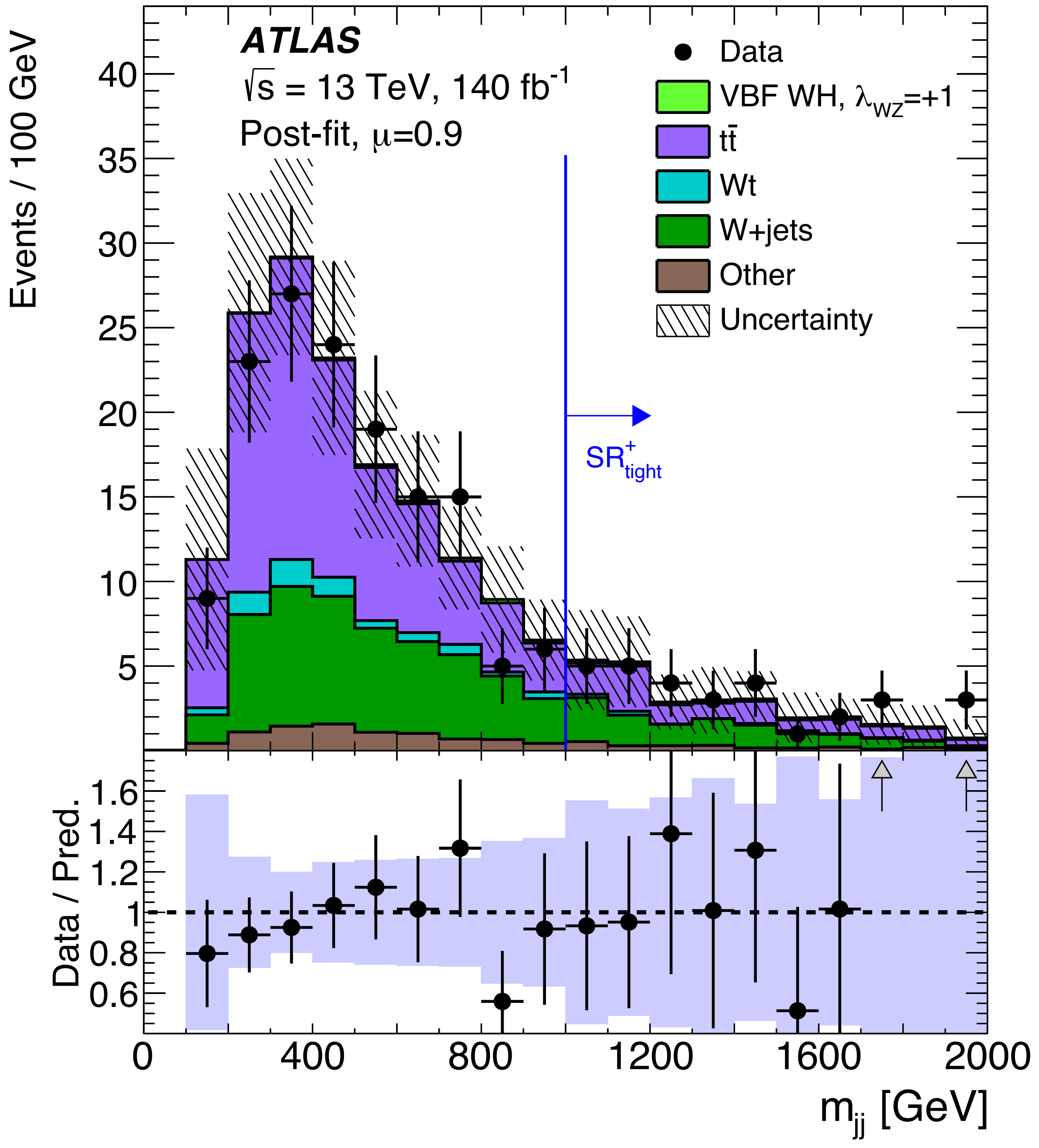
Variable	$t\bar{t}$ CR$^-$	$t\bar{t}$ CR$^+$	W+jets CR$^-$	W+jets CR$^+$	Wt CR$^-$	Wt CR$^+$
$m_{b\bar{b}}$	> 145 GeV	> 145 GeV	< 70 GeV	< 70 GeV	> 145 GeV	> 145 GeV
$\Delta R_{b\bar{b}}$	< 1.2	< 1.2	$< 2.23 - 0.007 p_T^{b\bar{b}}$/GeV	$< 2.23 - 0.007 p_T^{b\bar{b}}$/GeV	> 1.5	> 1.6
$p_T^{b\bar{b}}$	> 200 GeV	–	$\in (150, 250)$ GeV	> 80 GeV	> 250 GeV	> 180 GeV
m_{top}^{lep}	> 260 GeV	> 220 GeV	> 275 GeV	> 260 GeV	> 320 GeV	> 320 GeV
Δy_{jj}	$\in (3, 4.4)$	> 3	> 3	> 3	> 3	> 3
m_{jj}	–	$\in (400, 1000)$ GeV	–	> 500 GeV	–	> 500 GeV
N_{jets}^{veto}	–	< 2	–	< 1	–	< 2
p_T^W	–	< 350 GeV	–	–	> 250 GeV	> 250 GeV
m_T^W	–	–	–	< 200 GeV	–	–
p_T^{j1}	–	–	> 70 GeV	> 70 GeV	< 350 GeV	< 350 GeV

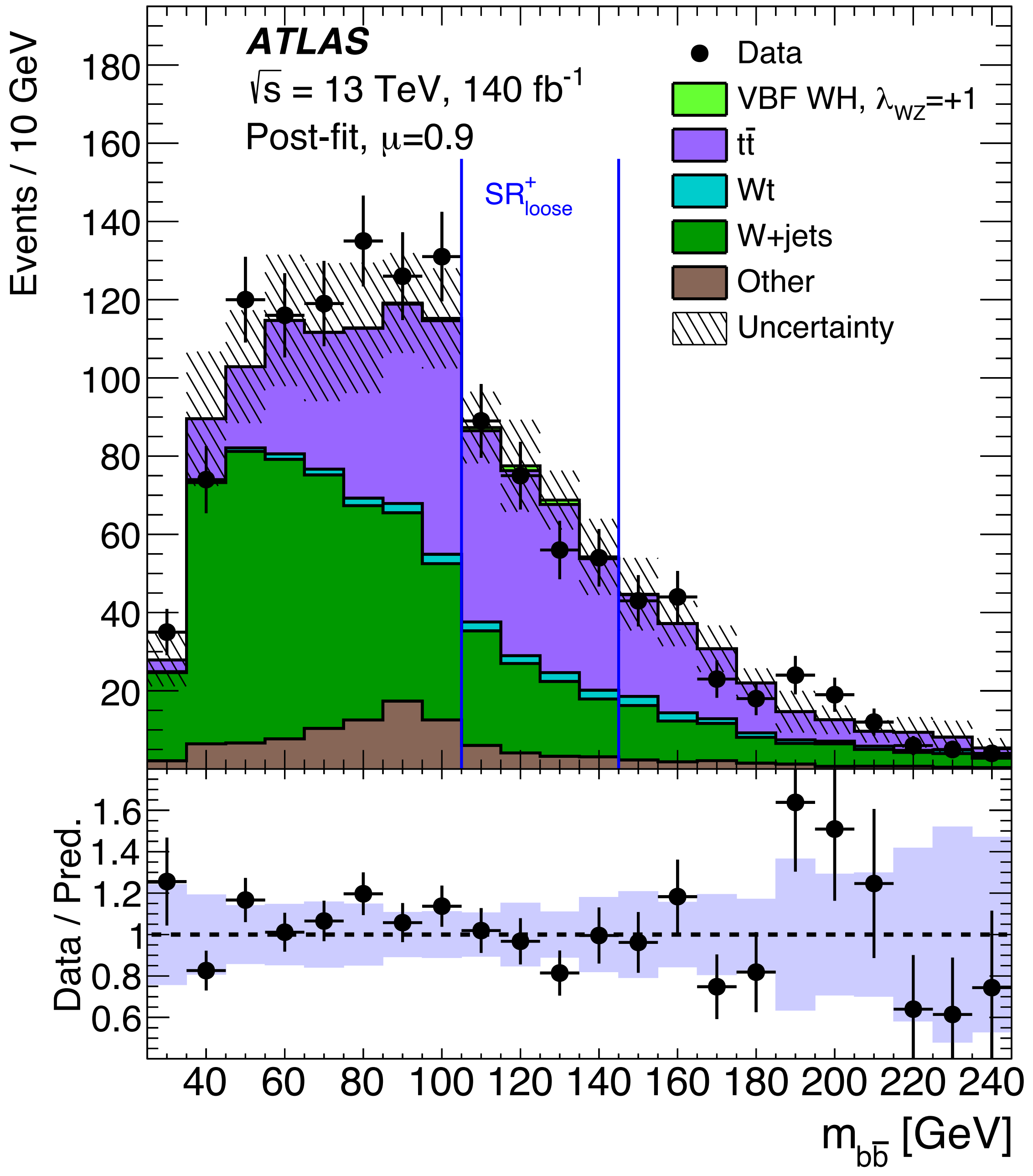
PRL 133.141801

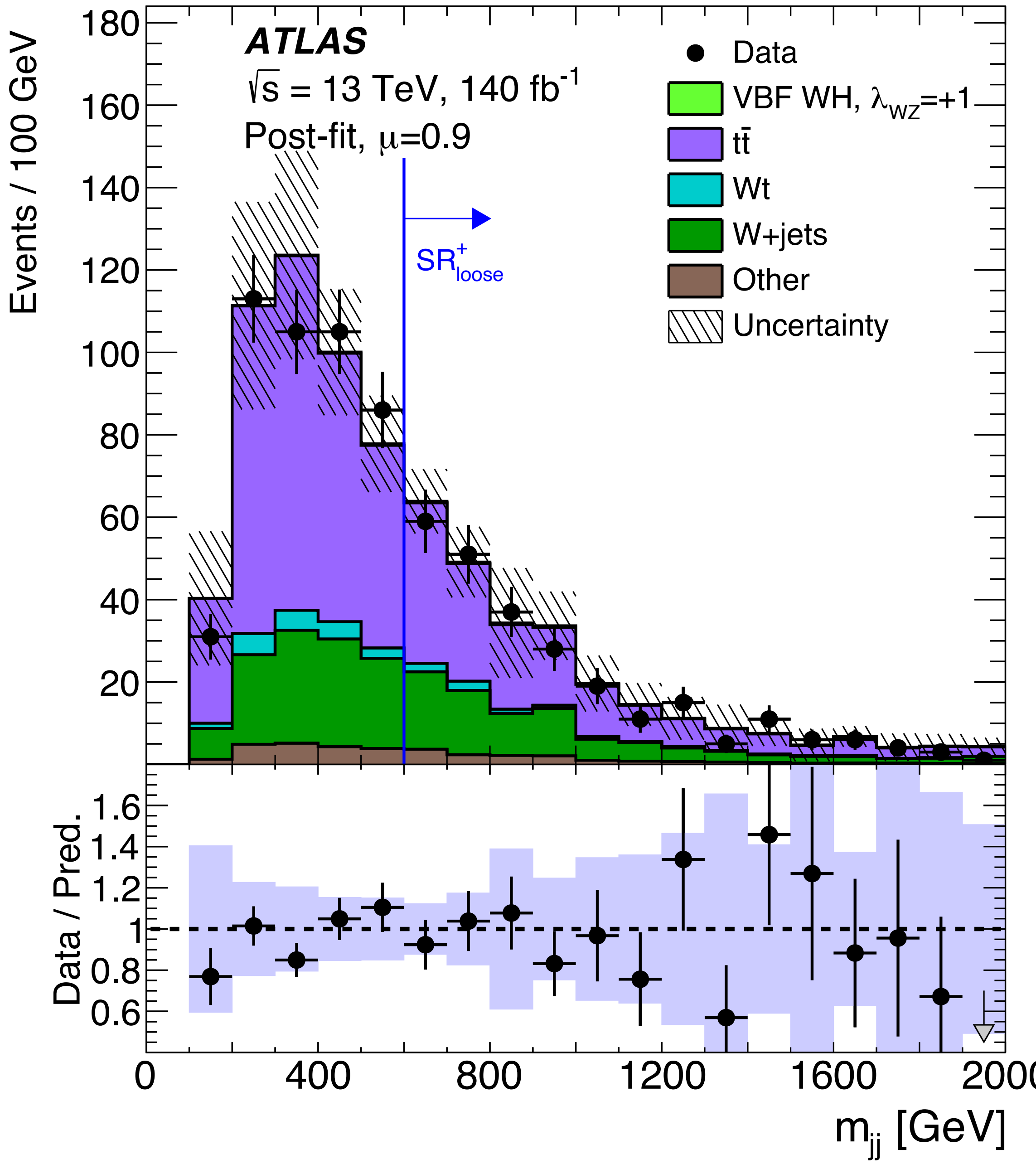
VBF WH(bb)

Postfit plots







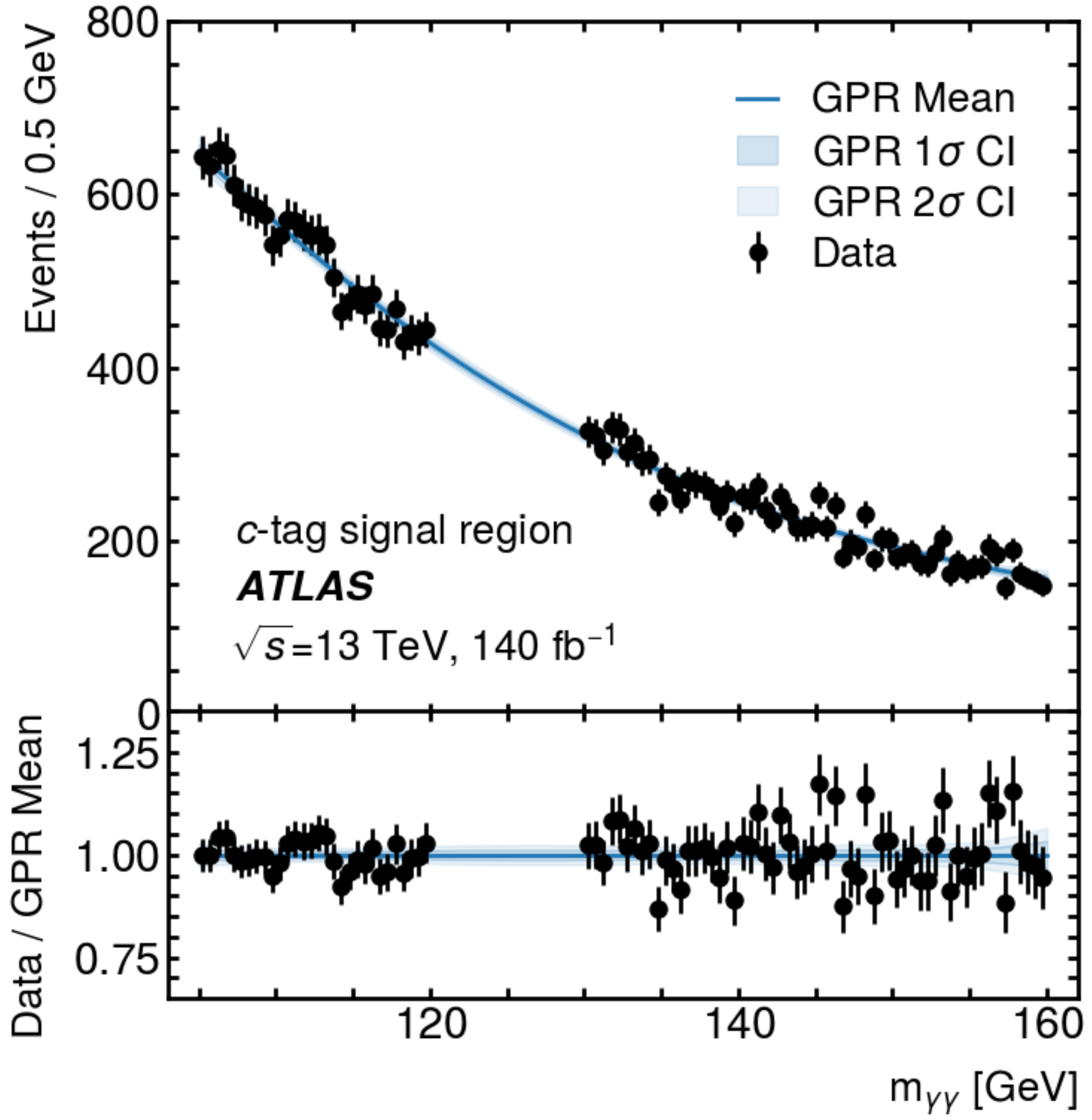


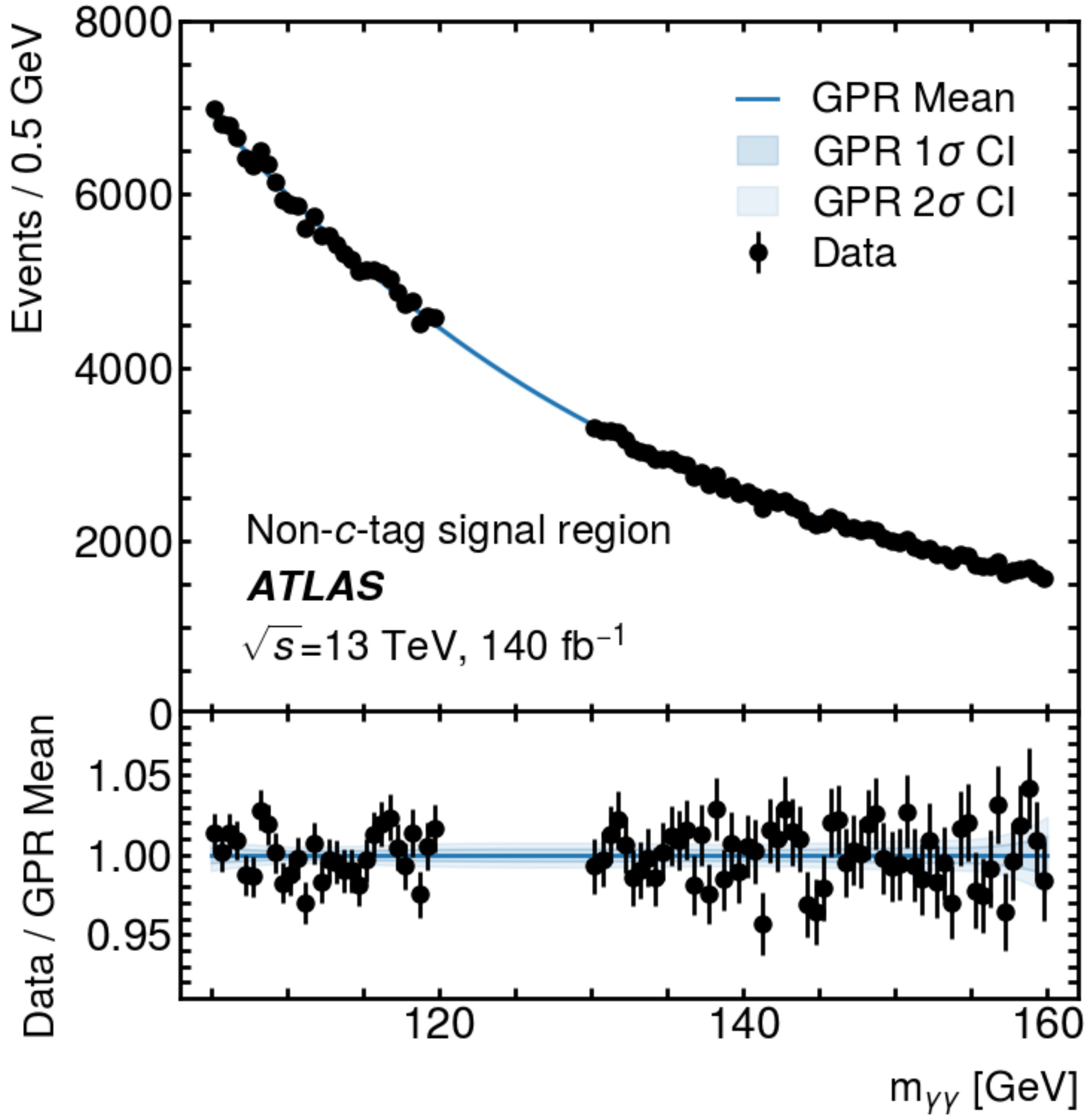
2407.15550

Inclusive H+c

Background modelling

- Main backgrounds: non-resonant $\gamma\gamma$, $\gamma + jet$ and di-jet processes
    - Use a data-driven approach based on Gaussian Process Regression (GPR)
- GPR method:
    - Linear preprocessing
    - Use GPR to estimate background in SR and full covariance matrix from data in sidebands
    - Binned likelihood fit to SR with GPR means as expected background



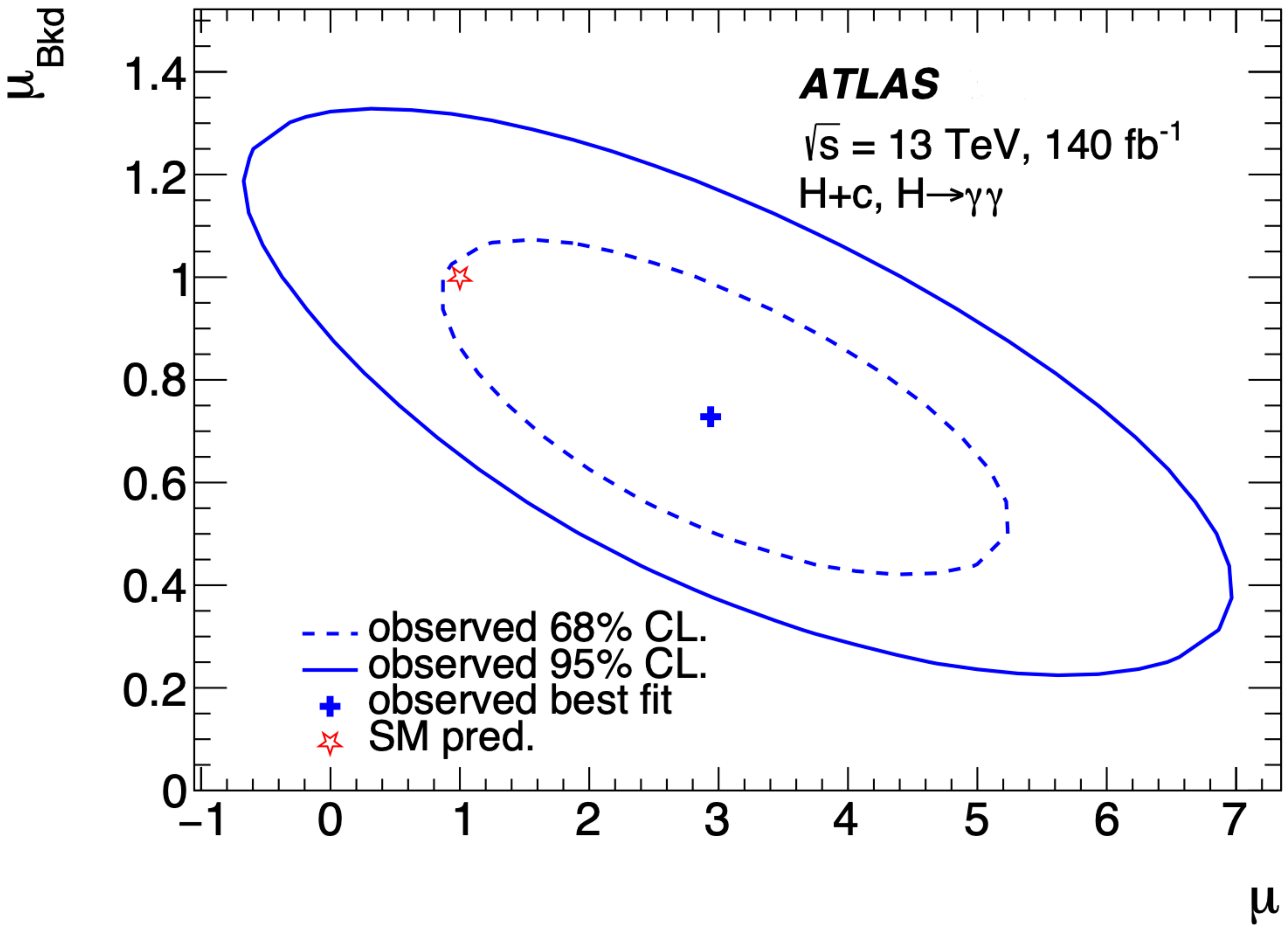


Inclusive H+c

Results

Process	c-tag signal region		Non-c-tag signal region	
	Signal	Resonant background	Signal	Resonant background
ggF H	39	82	110	1800
VBF H	17	13	34	220
WH	9.5	4.7	23	59
ZH	4.5	5.1	7.8	50
$t\bar{t}H$	7.0	4.6	20	24
$b\bar{b}H$	0.11	1.9	0.35	16
y_c-sensitive $H+c$	0.37	0.046	0.78	0.48

Approximate expected yields of different physics processes



Profile likelihood scan of μ_{signal} and μ_{bkg} on the observed data