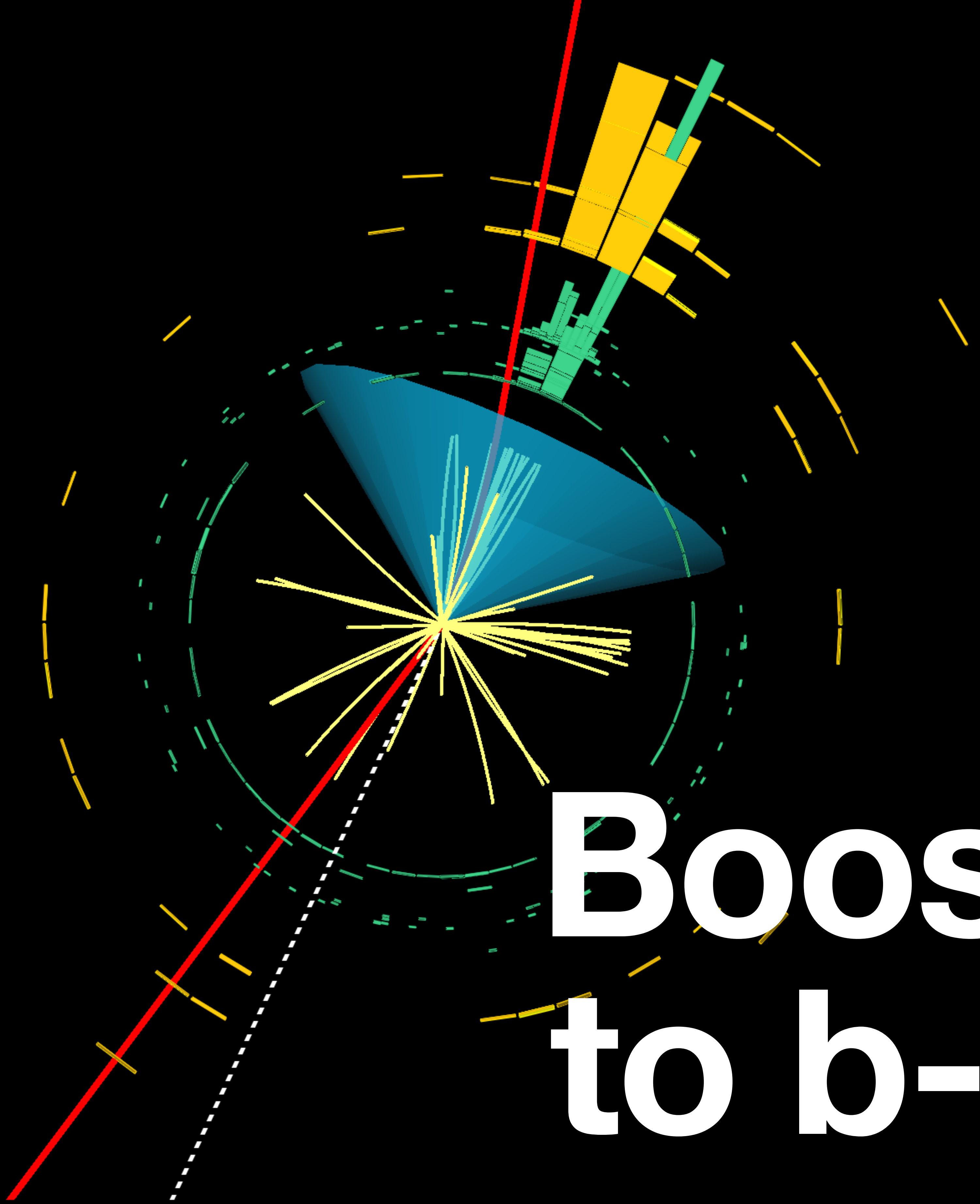
Boosted Higgs decay to b-quarks in ATLAS



Marion Missio

Higgs Hunting - 24 September 2024

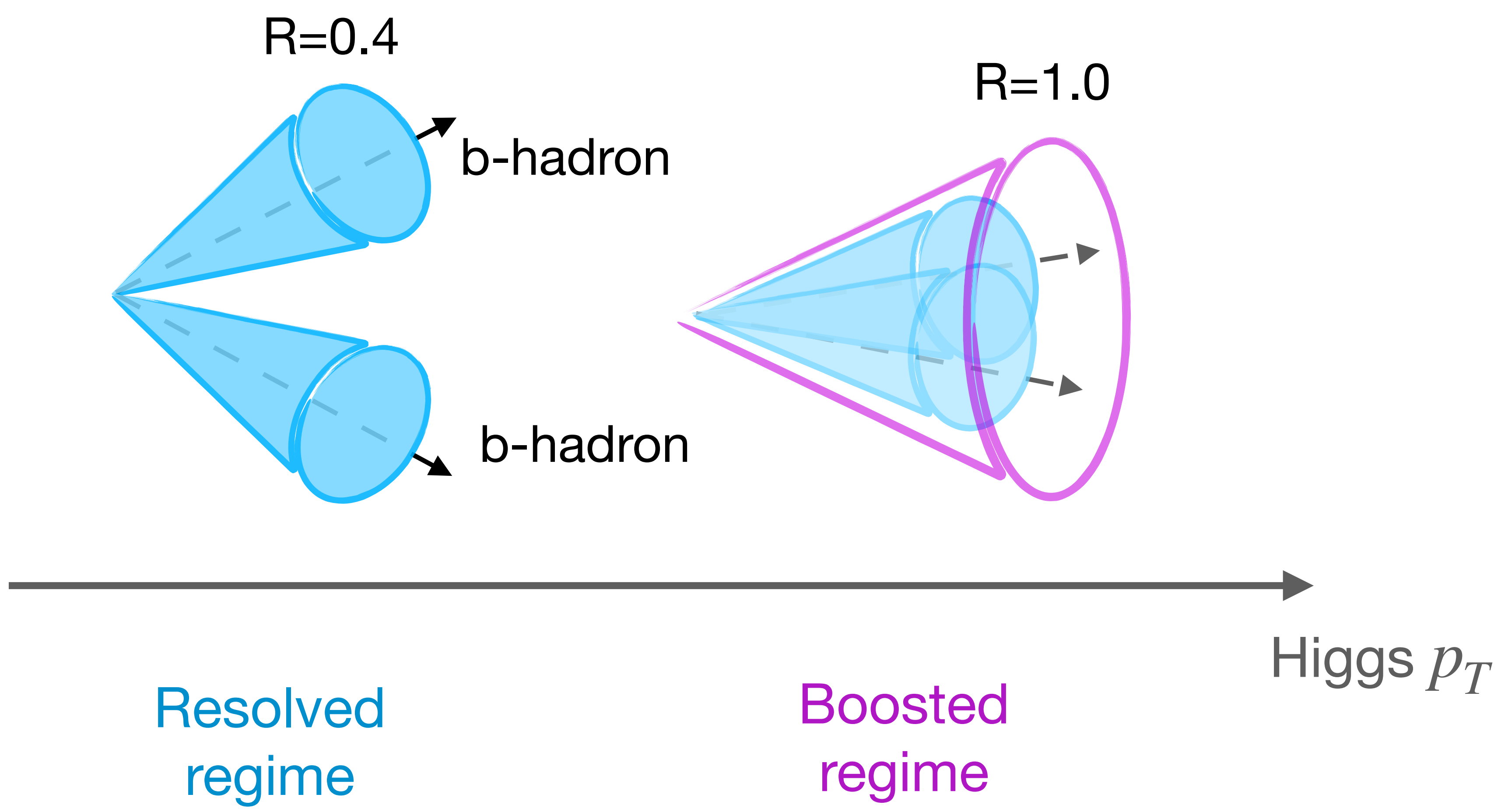
ATLAS EXPERIMENT

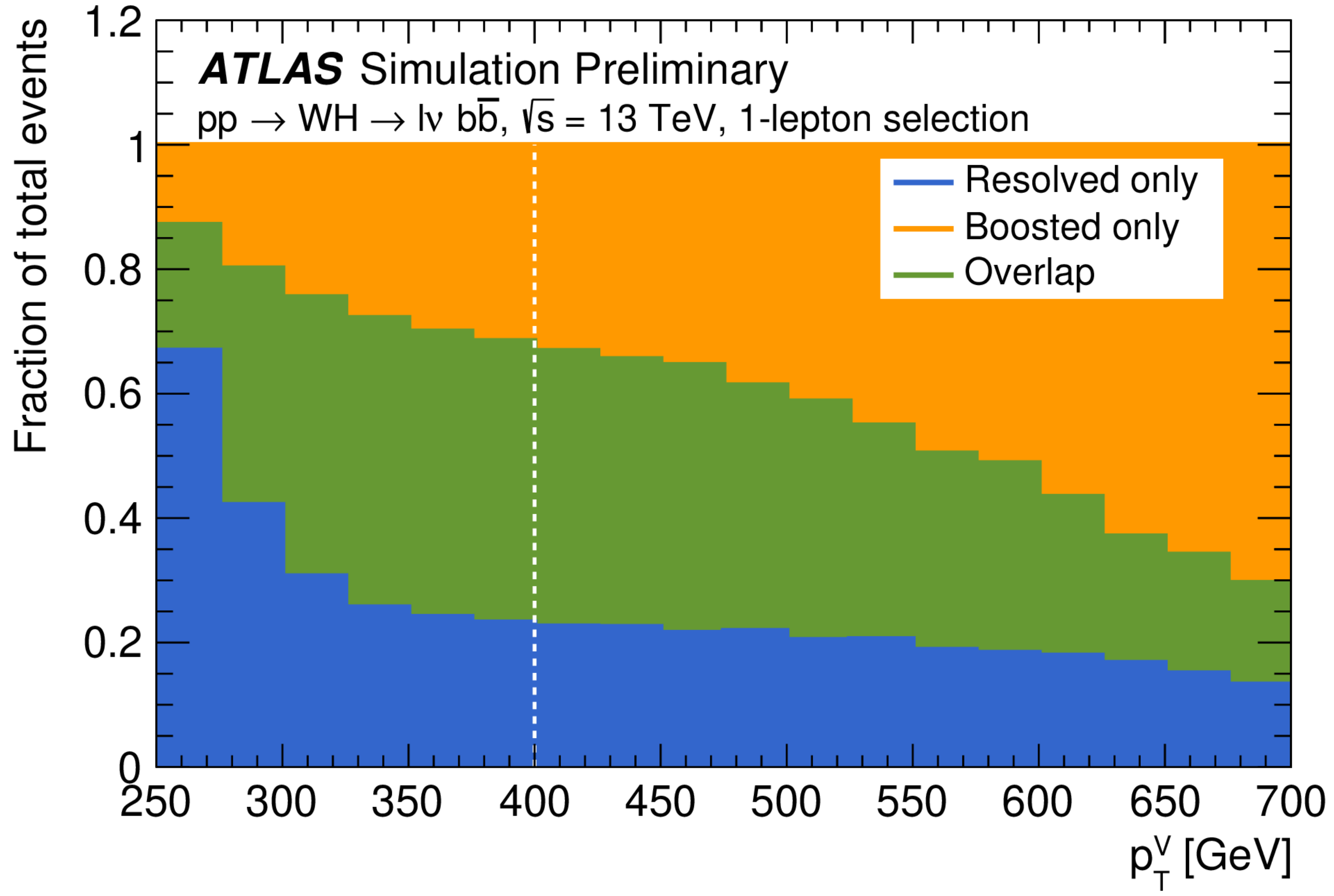
Nikhef

IN DEI NOMINE FELICITER

Introduction

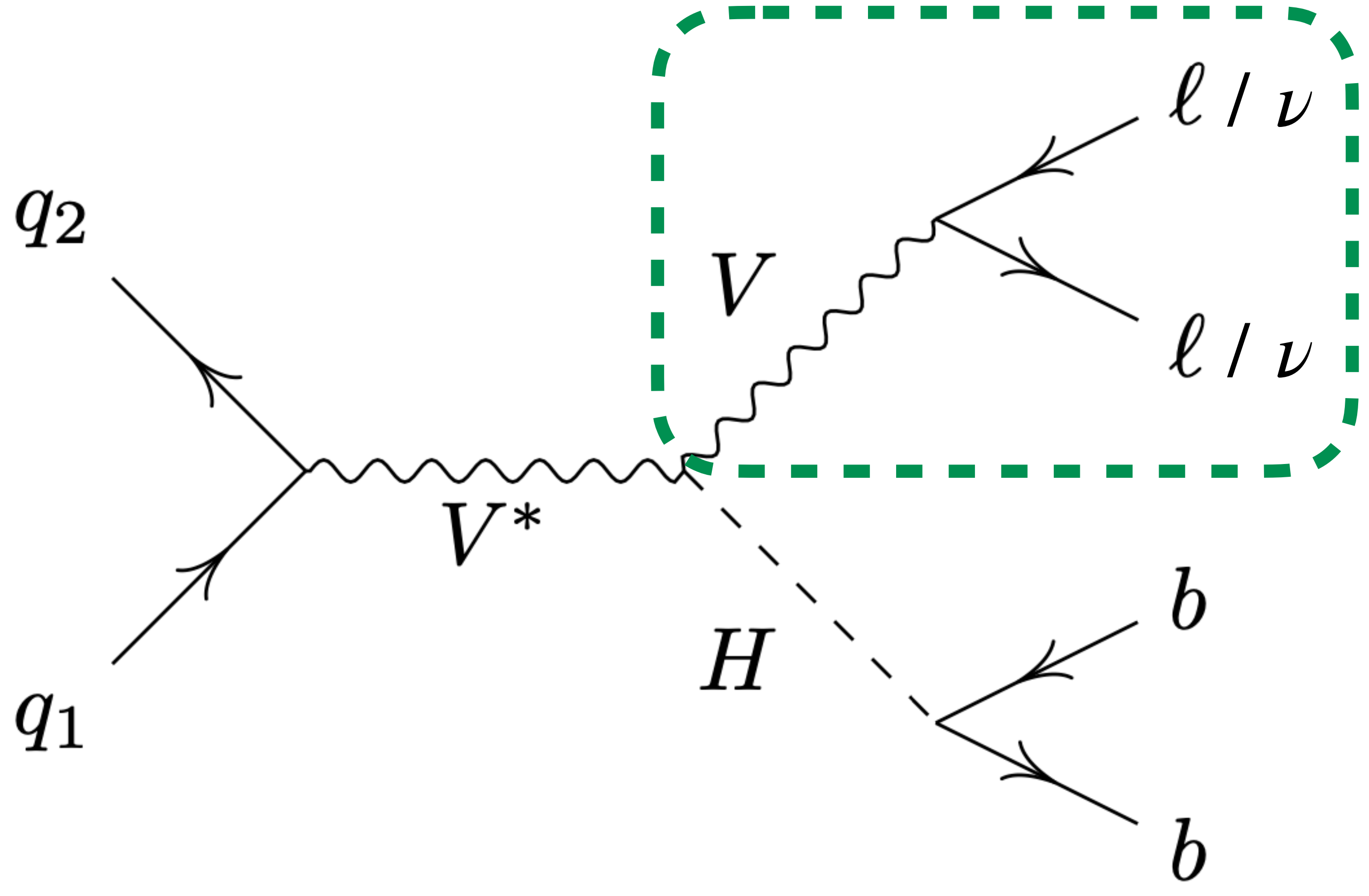
- H to $b\bar{b}$ has the largest branching ratio → large statistics to probe the high energy regime
  - Interesting regime due to its sensitivity to physics beyond the Standard Model
  - Higgs boson is reconstructed with a large-R jet

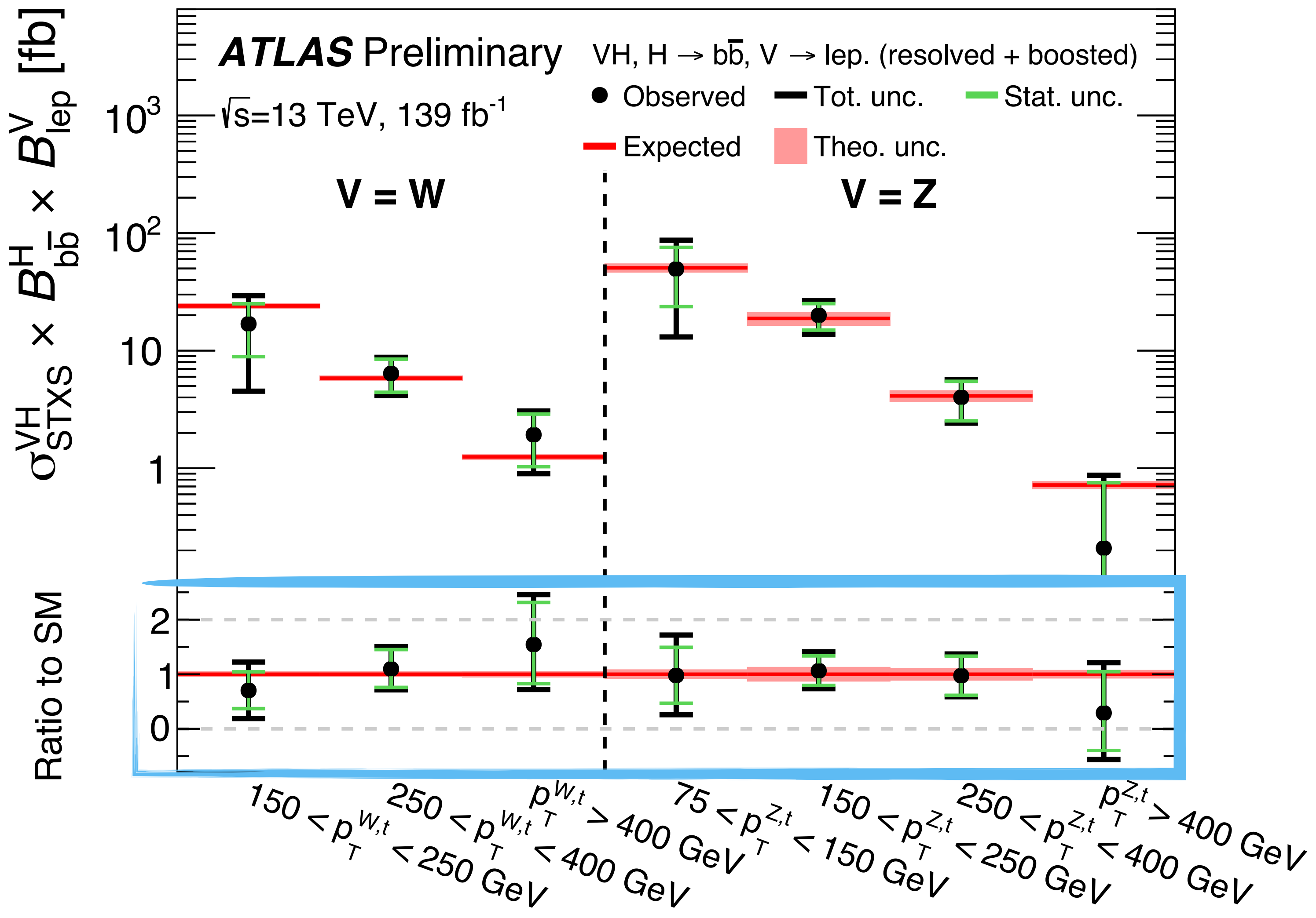




Introduction

- Search for H(bb) associated with a vector boson:
  - Reduce QCD multijet background and clean leptonically decay
  - 3 final states: $Z \rightarrow \nu\nu$ (0L), $W \rightarrow l\nu$ (1L) and $Z \rightarrow ll$ (2L) with e, μ or τ (1L) as leptons
- A first full Run2 standalone and <u>combination</u> analyses were already performed
  - Agreement within 1σ with the SM expectation
  - New result from a second full Run2 analysis is available → will be discussed in these slides





ATL-COM-PHYS-2021-300

New VH(bb/cc) analysis

- New analysis with simultaneous measurement of VH(bb) and VH(cc) with a fully coherent strategy → **this talk will focus on the high p_T regime of VH(bb)**
- Significant changes were made to this new analysis

New VH(bb/cc) analysis

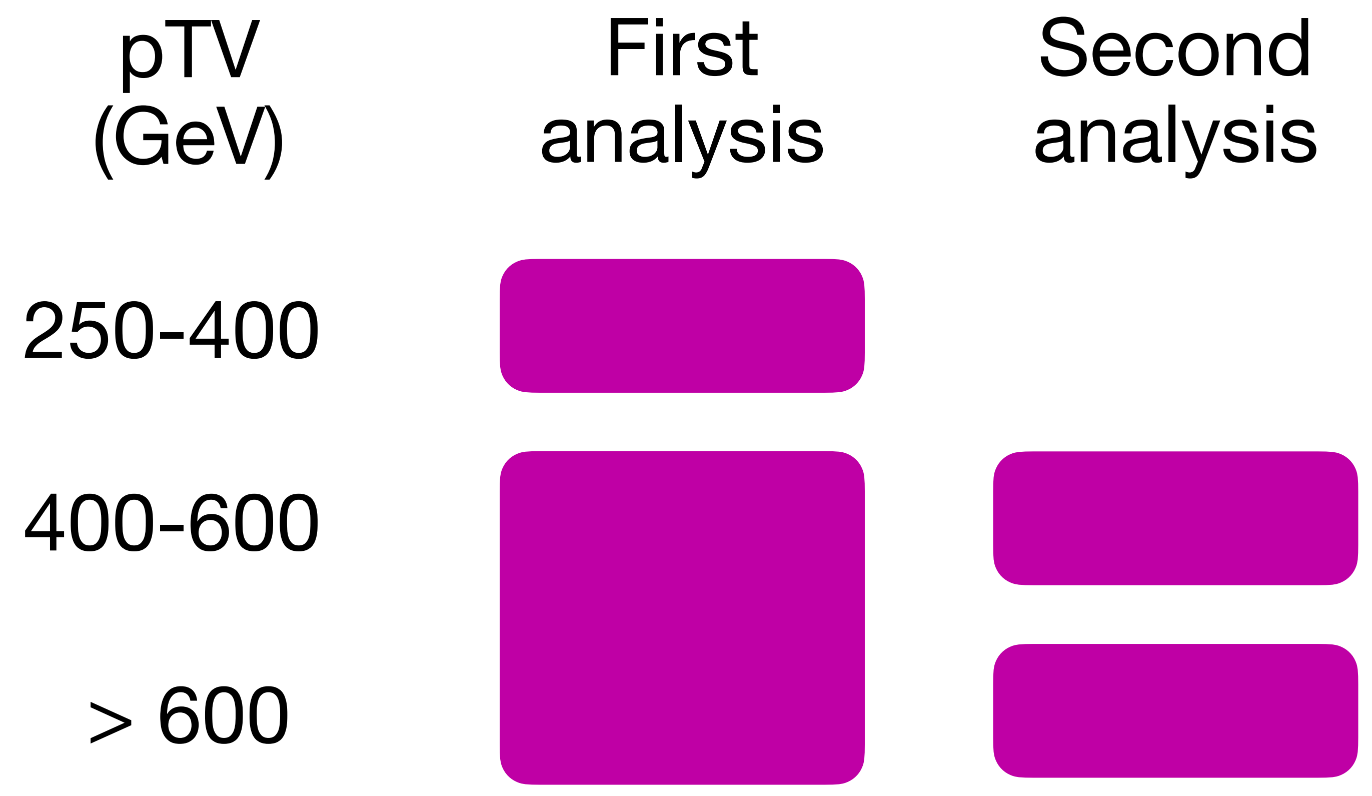
- New analysis with simultaneous measurement of VH(bb) and VH(cc) with a fully coherent strategy → **this talk will focus on the high p_T regime of VH(bb)**
- Significant changes were made to this new analysis:
  - Fit BDT discriminant → (full syst.) significance improved up to 50%

New VH(bb/cc) analysis

- New analysis with simultaneous measurement of VH(bb) and VH(cc) with a fully coherent strategy → **this talk will focus on the high p_T regime of VH(bb)**
- Significant changes were made to this new analysis:
  - Fit BDT discriminant
  - Improved flavour tagging and tagging strategy: at same b-jet efficiency, it has better c-jet and light-jet rejections → can use a looser working point to recover more signal events

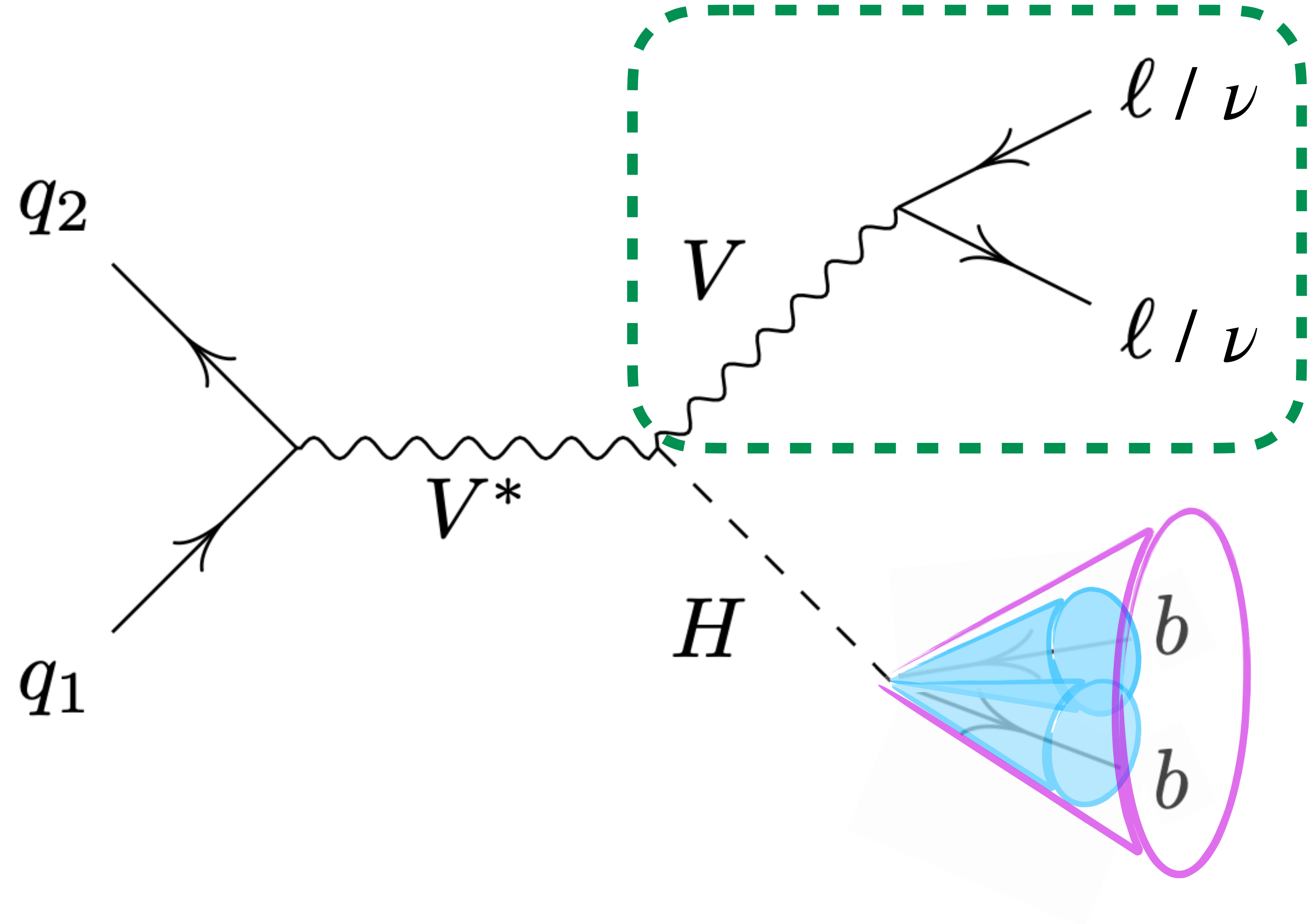
New VH(bb/cc) analysis

- New analysis with simultaneous measurement of VH(bb) and VH(cc) with a fully coherent strategy → **this talk will focus on the high p_T regime of VH(bb)**
- Significant changes were made to this new analysis:
  - Fit BDT discriminant
  - Improved flavour tagging and tagging strategy
  - Different analysis regions:



Event reconstruction and selection

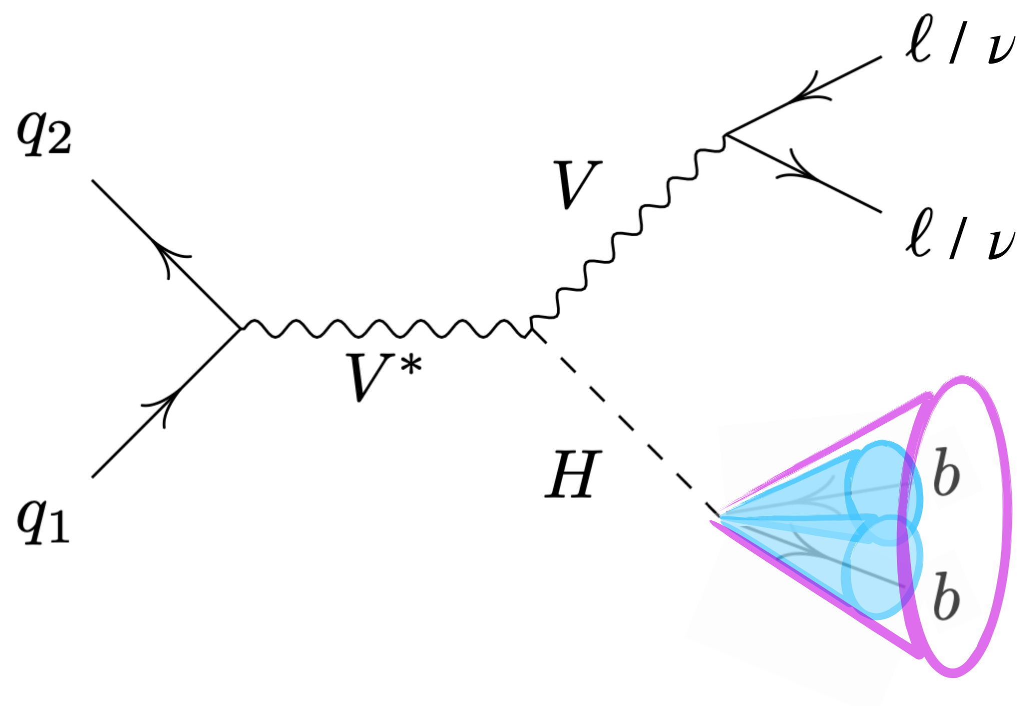
- Vector boson: trigger based on missing transverse energy or single electron for 1L and 2L
  - Event selected with $p_T^V > 400$ GeV
- Higgs boson: calorimeter jet collection clustered with anti-k_t algorithm with R=1.0
  - Event selected with $p_T > 250$ GeV and $m_J > 50$ GeV
- Track-jets: built with anti-k_t algorithm with variable radius and used to reconstruct the b-tagged objects
  - At least 2 track-jets associated with the large-R jet with $p_T > 10$ GeV

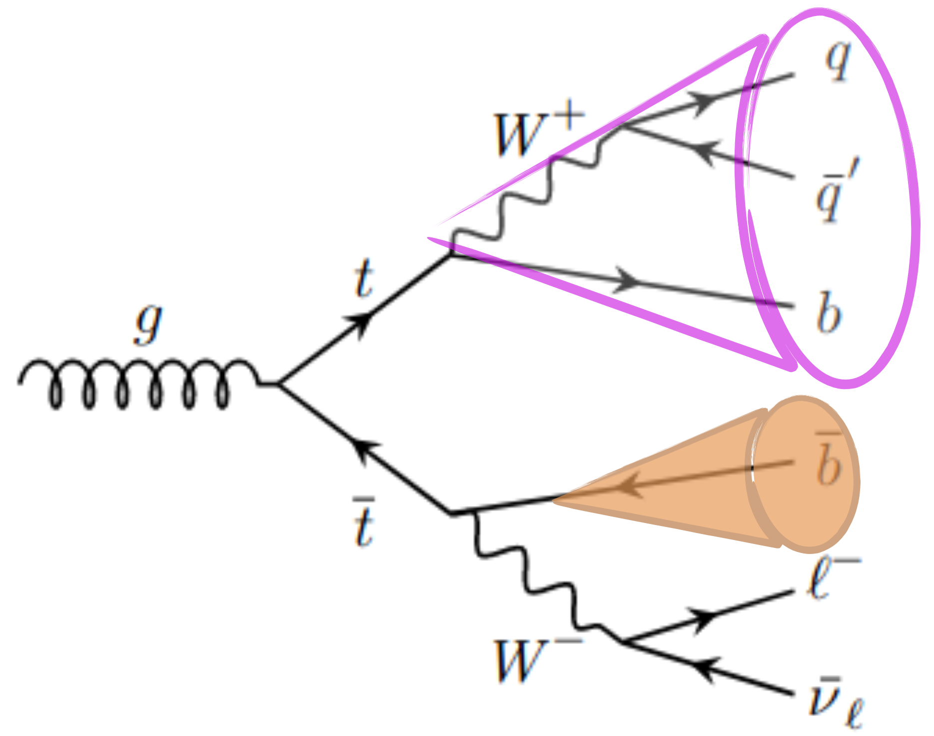


Nikhef

Analysis regions

- Regions are split between lepton channels, p_T^V and signal/control regions → **8 regions in total**
- Signal region:
  - exactly 2 out of the 3 leading track-jets inside the large-R jet have to be b-tagged
  - no b-tagged track-jet outside the large-R jet
- Control region → used to constrain top process:
  - Requires one b-tagged track-jet outside the large-R jet

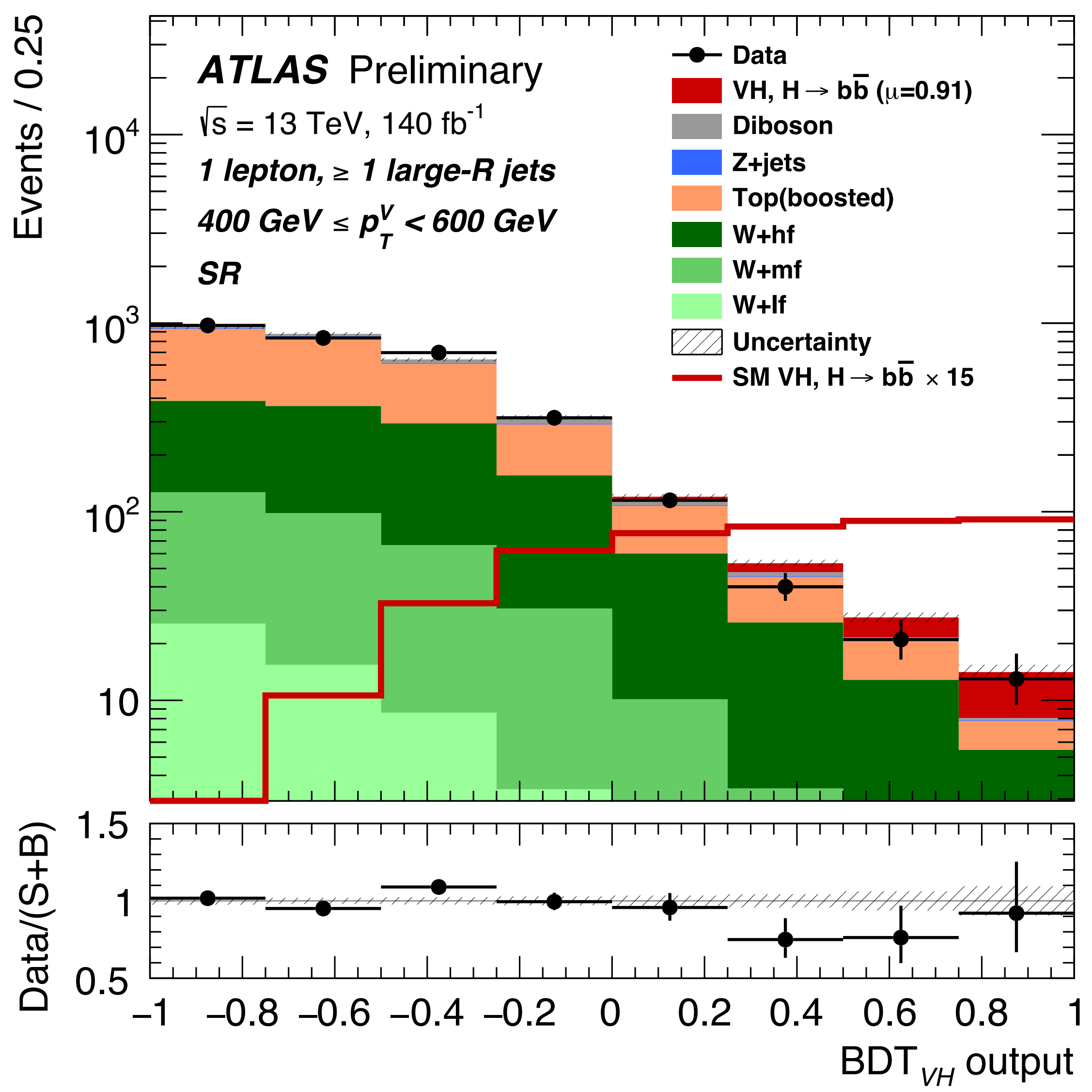


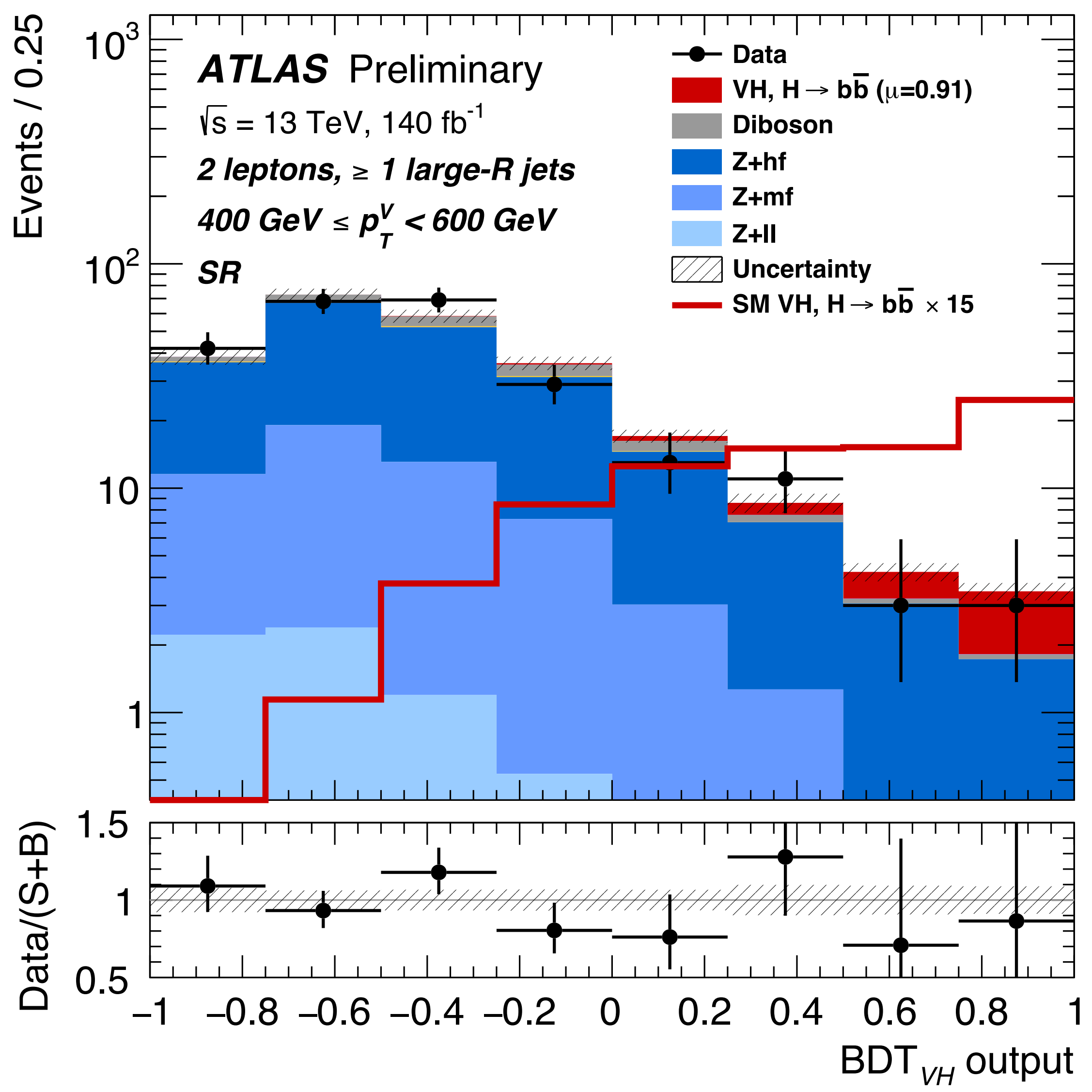


Nikhef

Modelling background

- Main backgrounds are W+jets and Top for 0L/1L and Z+jets for 0L/2L
  - Modelled with Monte-Carlo (MC) simulation
- Floating normalisation extracted from the fit with the help of control region
- Acceptance and shape uncertainties are derived by comparison from MC samples
  - Between nominal with varied parameters stored as internal weights
  - Between nominal and alternative samples



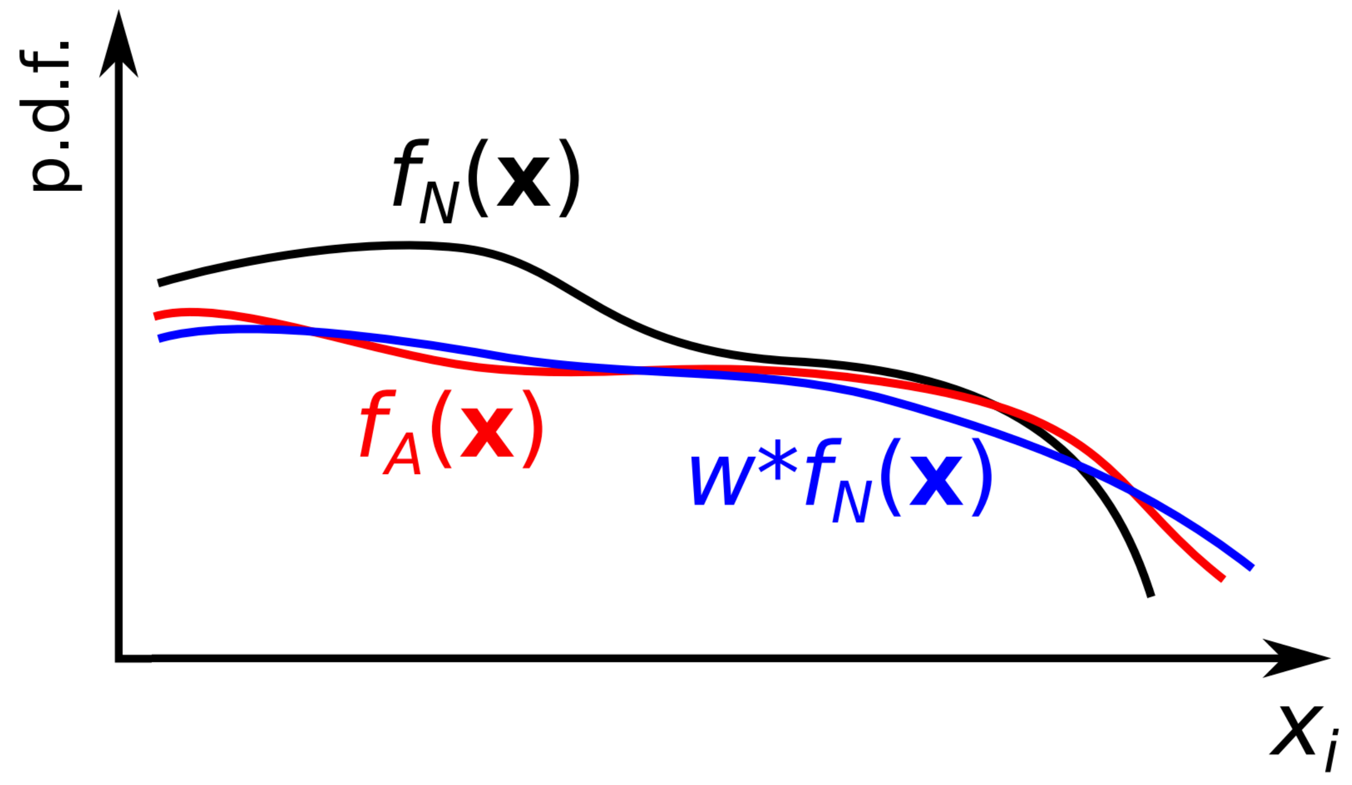


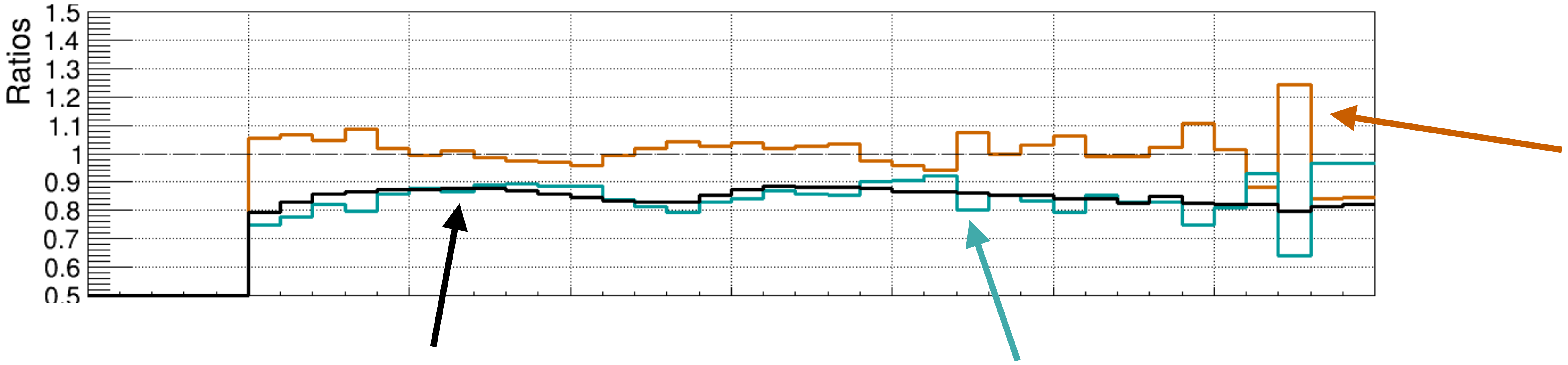
Nikhef

Modelling background

- 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

Shape from CARL

Shape from alternative

MVA techniques

- Use of BDT to discriminate signal from background → **new for this analysis**
- Optimisation started from with the input variables used in the previous VH(bb) low p_T regime:
  - Different sets of variables for each lepton channels
  - Tested many variables → kept only the ones that bring significant improvement

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

Results

- Changes made in this analysis bring an increase in the expected significance

First full Run2 analysis

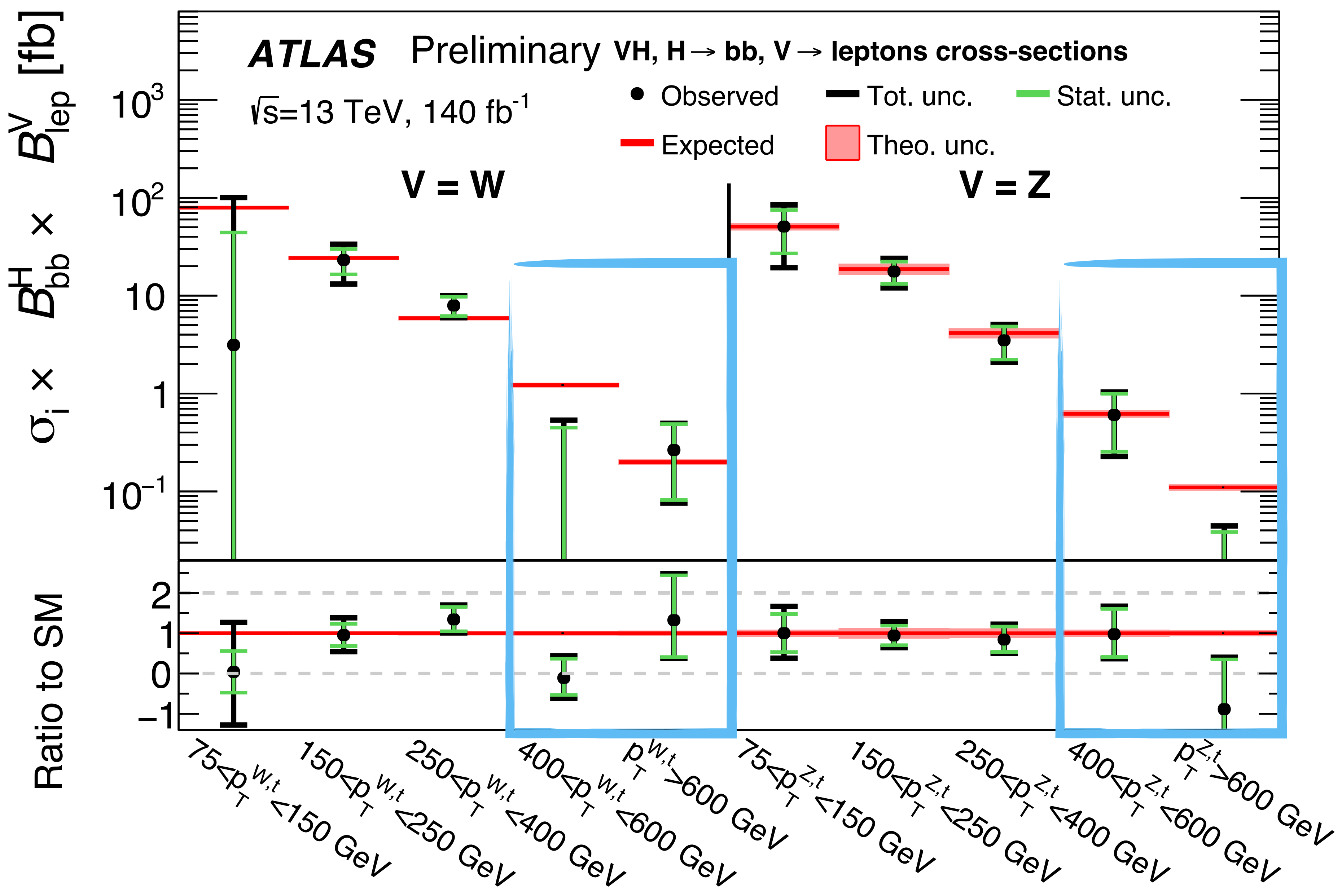
Measurement	Expected sig.
WH $[400, \infty]$ GeV	1.27
ZH $[400, \infty]$ GeV	1.12

Second full Run2 analysis

STXS region	post-fit expected
WH, 400 GeV $< p_{\mathrm{T}}^{V,t} <$ 600 GeV	1.6 σ
WH, $p_{\mathrm{T}}^{V,t} >$ 600 GeV	1.0 σ
ZH, 400 GeV $< p_{\mathrm{T}}^{V,t} <$ 600 GeV	1.7 σ
ZH, $p_{\mathrm{T}}^{V,t} >$ 600 GeV	0.8 σ

Results

- Changes made in this analysis bring an increase in the expected significance
- Simplified Higgs template cross-section (STXS): measurement split in p_T^V bins
- Largest uncertainties come from data statistical uncertainty
- Good agreement with the SM expectation
  - Deviations are less than 2σ for the high p_T regime



Nikhef

Summary

- Performed a final full Run2 analysis for VH(bb) at high p_T regime for $p_T^V > 400$ GeV
- STXS measurements were performed $\rightarrow$ good agreement with the SM prediction: deviations are less than 2σ
  - Changes like addition of BDT or increase of MC statistics with CARL bring improvement compared to the first full Run2 analysis
- Conference note is already available, publication will follow shortly

Thank you for your attention!

ATLAS EXPERIMENT

Nikhef

IN·DEI·NOMINE·FELICITER

Selection

Objects selection

Electron Selection	p_T	η	ID	d_0^{sig} w.r.t. BL	$\|\Delta z_0 \sin\theta\|$	Isolation
VH-Loose	>7 GeV	$\|\eta\| < 2.47$	LH Loose	< 5	< 0.5 mm	Loose_VarRad
ZH-Signal	>27 GeV	Same as VH-Loose				
WH-Signal	Same as ZH-Signal		LH Tight	Same as ZH-Signal		HighPtCaloOnly

Table 3: Electron selection requirements

Muon Selection	p_T	η	ID	d_0^{sig} w.r.t. BL	$\|\Delta z_0 \sin\theta\|$	Isolation
VH-Loose	>7 GeV	$\|\eta\| < 2.7$	Loose quality	< 3	< 0.5 mm	Loose_VarRad
ZH-Signal	>27 GeV	$\|\eta\| < 2.5$	Same as VH-Loose			
WH-Signal	>25 GeV when $p_T^V > 150$ GeV >27 GeV when $p_T^V < 150$ GeV	$\|\eta\| < 2.5$	Medium quality	< 3	< 0.5 mm	HighPtTrackOnly

Table 4: Muon selection requirements

Lepton	p_T	η	n_{trk}	ID
tau	>20 GeV	$\|\eta\| < 2.5$	1 or 3 tracks	Loose

Table 5: Hadronic tau selection requirements

Jet Category	Selection Requirements
Large-R jets	$p_T > 250$ GeV $\|\eta\| < 2.0$
Track jets	$p_T > 10$ GeV $\|\eta\| < 2.5$

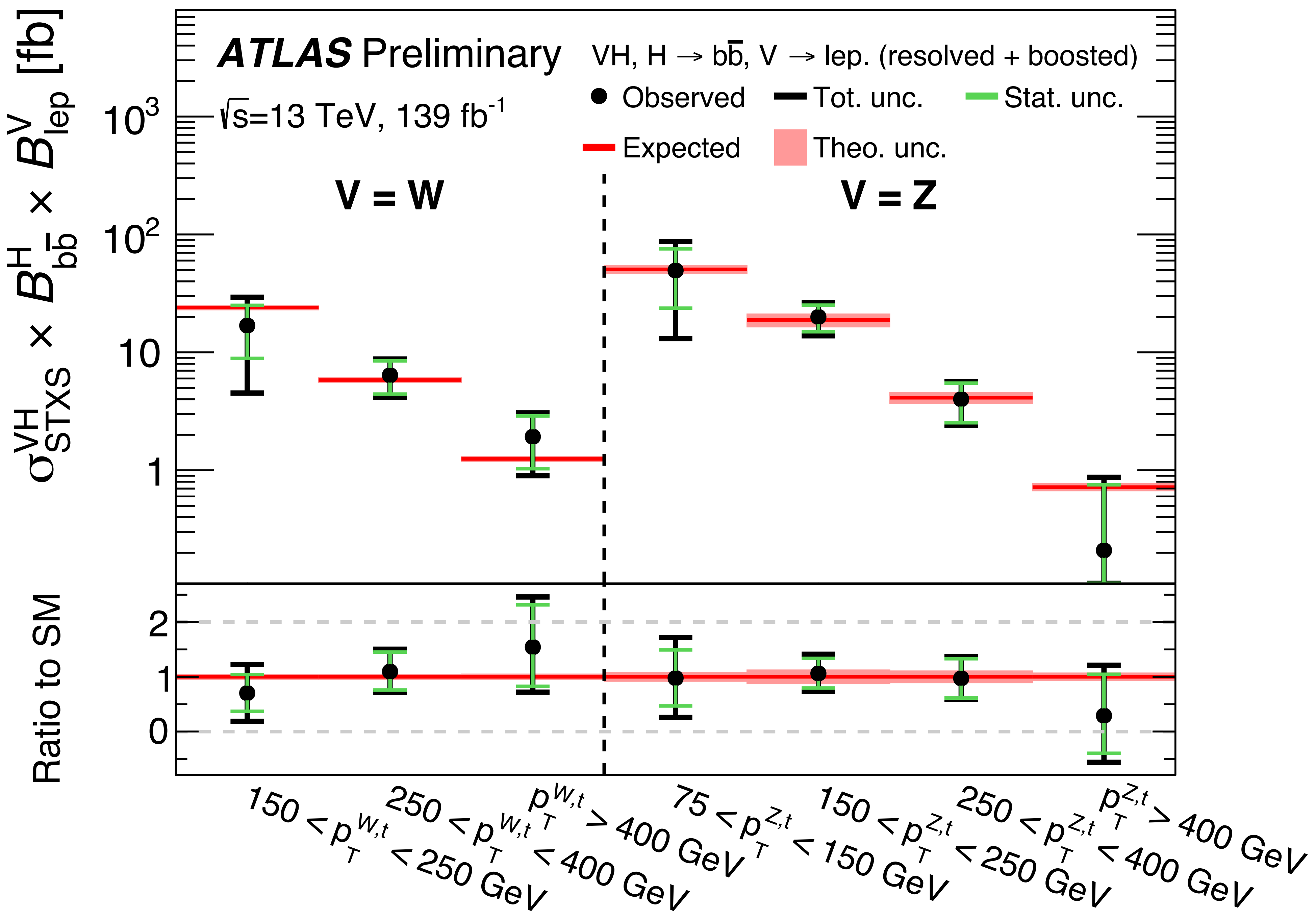
Table 7: Summary of the large-R jets and VR jets selections.

Event selection

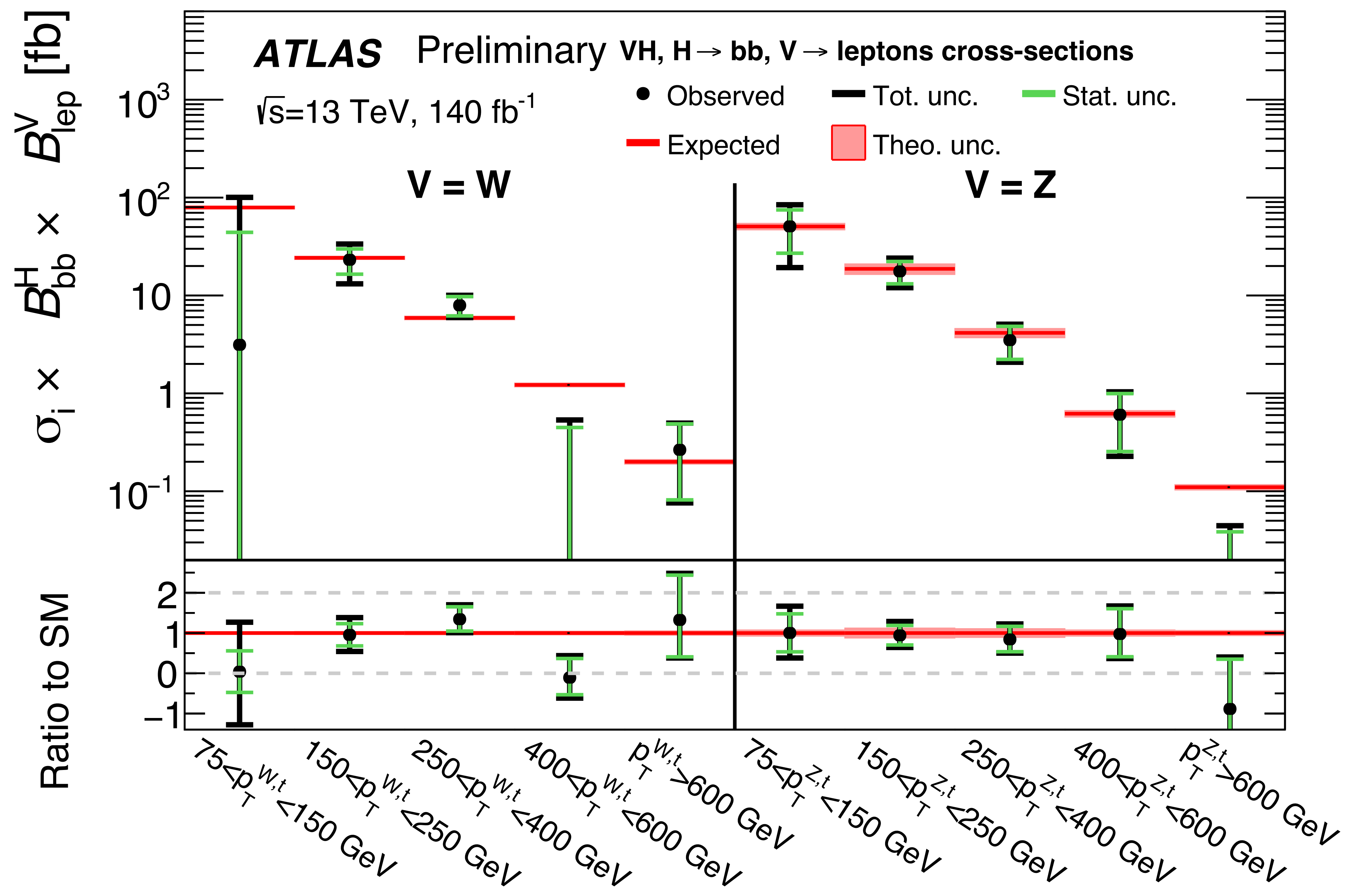
Selection	0 lepton channel	1 lepton channel		2 lepton channel	
		e sub-channel	μ sub-channel	e sub-channel	μ sub-channel
Trigger	E_T^{miss}	Single electron	E_T^{miss}	Single electron	E_T^{miss}
Leptons	0 VH-*loose* lepton	1 WH-*signal* lepton no second VH-*loose* lepton no hadronic τ		≥ 1 ZH-*signal* lepton 2 VH-*loose* leptons	
E_T^{miss}	> 250 GeV	> 50GeV	-	-	
p_T^V	$p_T^V > 400$ GeV				
Large-R jet	at least one large-R jet, $p_T > 250$ GeV, $\|\eta\| < 2$				
Track-Jets	at least two track-jets, $p_T > 10$ GeV, $\|\eta\| < 2.5$, matched to the leading large-R jet				
b-jets	exactly two of the leading three track-jets matched to the leading large-R must be b-tagged				
m_J	> 50 GeV				
$\min \Delta\phi(E_T^{miss}, \text{jets})$	> 30°	-			
$\Delta\phi(E_T^{miss}, H_{cand})$	> 120°	-			
$m_{\ell\ell}$	-			66 GeV< $m_{\ell\ell}$ < 116 GeV	
lepton flavor	-			two lepton same flavour	
lepton charge	-			opposite sign muons	

Comparison between full Run2 analyses

First full Run2 analysis



Second full Run2 analysis



Comparison between full Run2 analyses

First full Run2 analysis

Measurement	Expected sig.
WH [250, 400] GeV	1.26
WH [400, ∞] GeV	1.27
ZH [250, 400] GeV	1.38
ZH [400, ∞] GeV	1.12

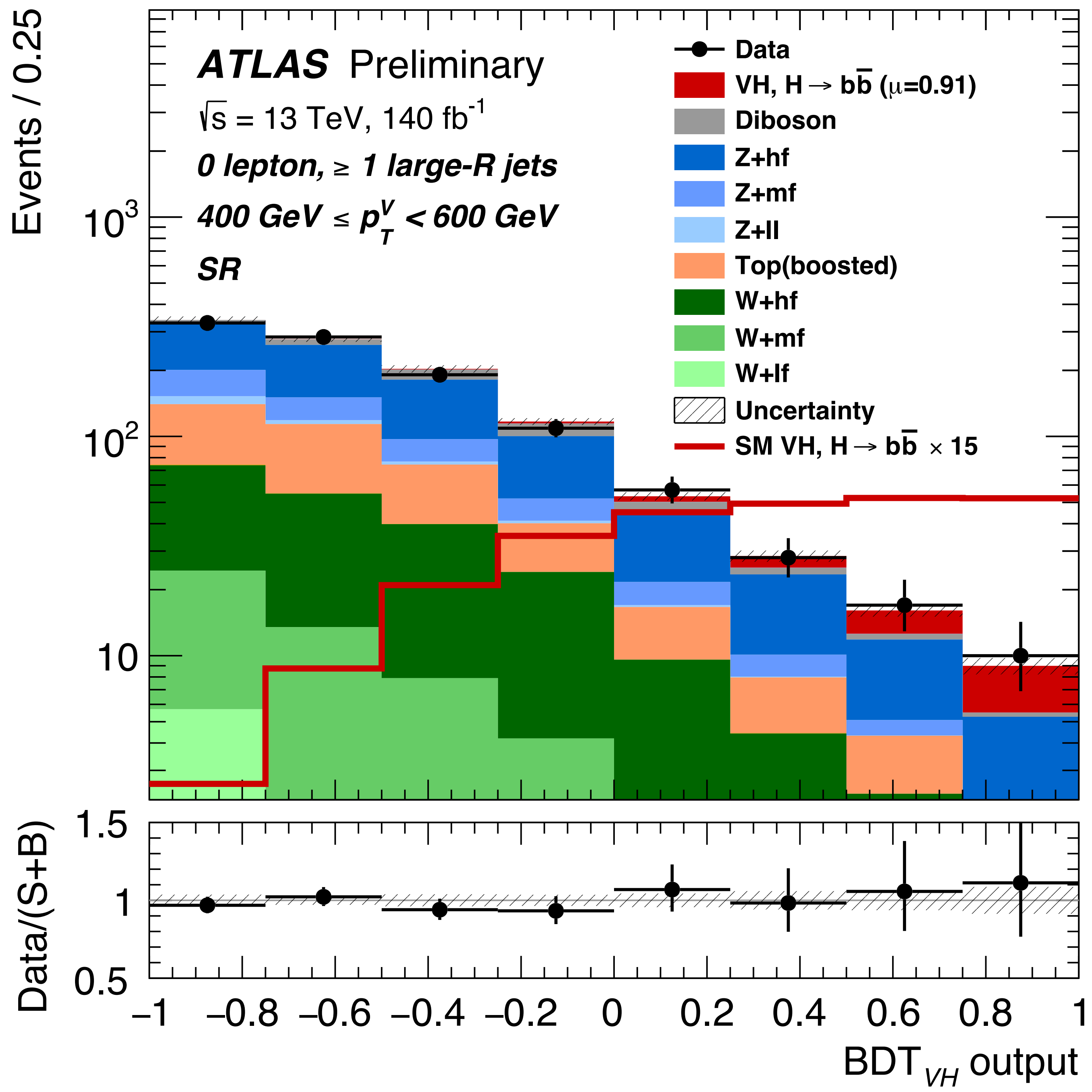
Second full Run2 analysis

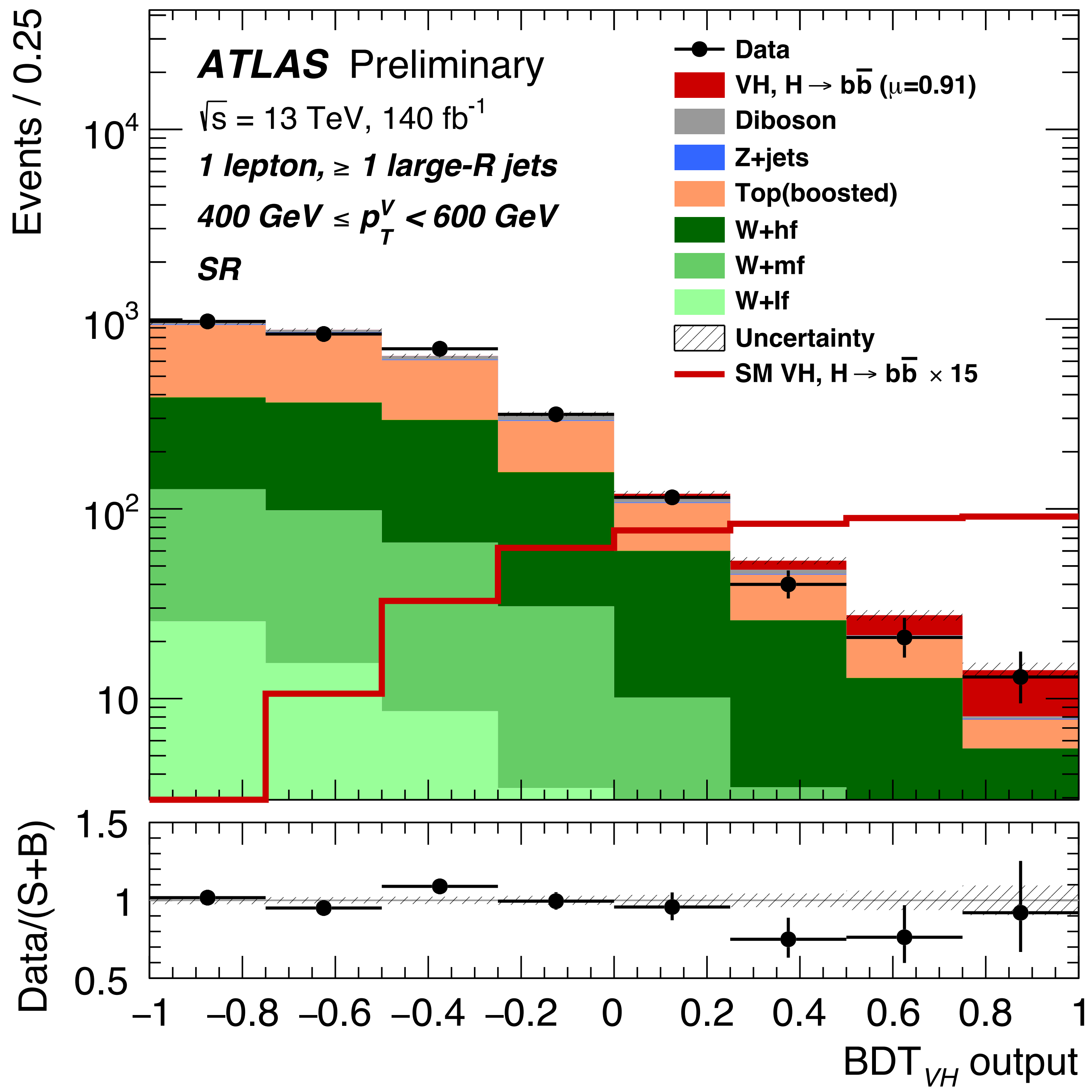
STXS region	post-fit expected
WH, 75 GeV $< p_{\mathrm{T}}^{V,t} <$ 150 GeV	0.7 σ
WH, 150 GeV $< p_{\mathrm{T}}^{V,t} <$ 250 GeV	2.4 σ
WH, 250 GeV $< p_{\mathrm{T}}^{V,t} <$ 400 GeV	3.2 σ
WH, 400 GeV $< p_{\mathrm{T}}^{V,t} <$ 600 GeV	1.6 σ
WH, $p_{\mathrm{T}}^{V,t} >$ 600 GeV	1.0 σ
ZH, 75 GeV $< p_{\mathrm{T}}^{V,t} <$ 150 GeV	1.6 σ
ZH, 150 GeV $< p_{\mathrm{T}}^{V,t} <$ 250 GeV	3.5 σ
ZH, 250 GeV $< p_{\mathrm{T}}^{V,t} <$ 400 GeV	3.3 σ
ZH, 400 GeV $< p_{\mathrm{T}}^{V,t} <$ 600 GeV	1.7 σ
ZH, $p_{\mathrm{T}}^{V,t} >$ 600 GeV	0.8 σ

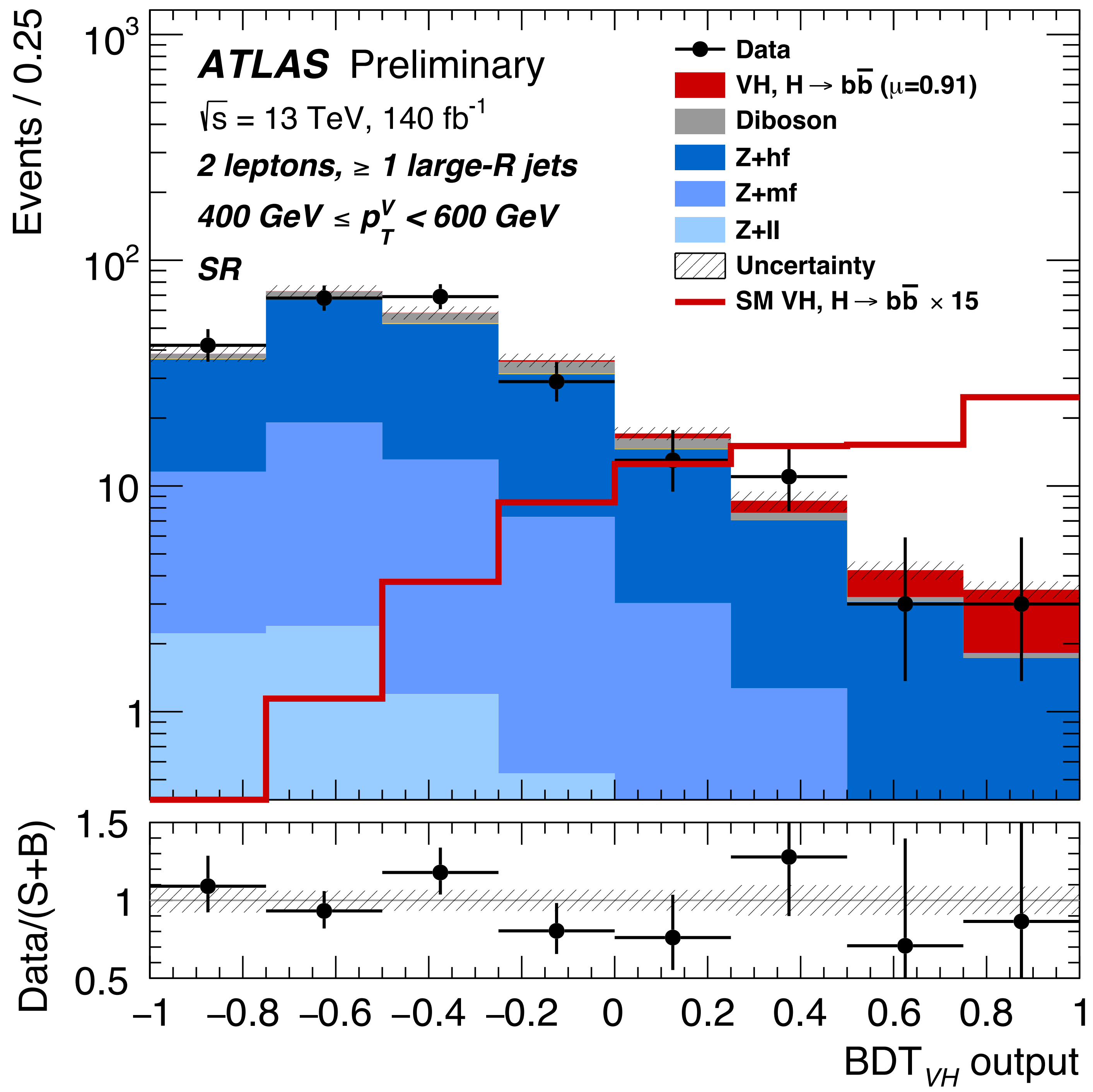
Expected significance for the high p_T regime

Postfit plots

400 < pTV < 600 GeV



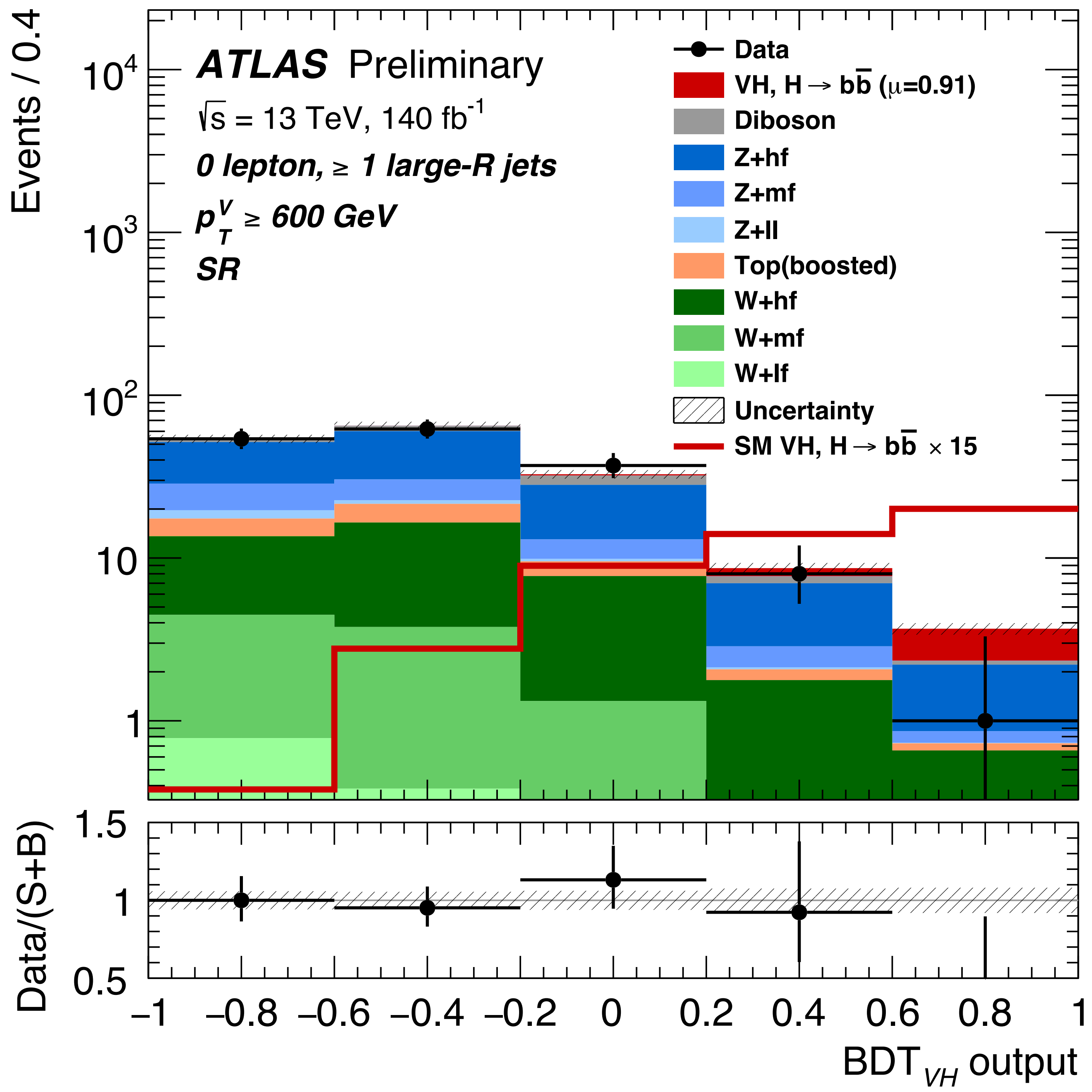


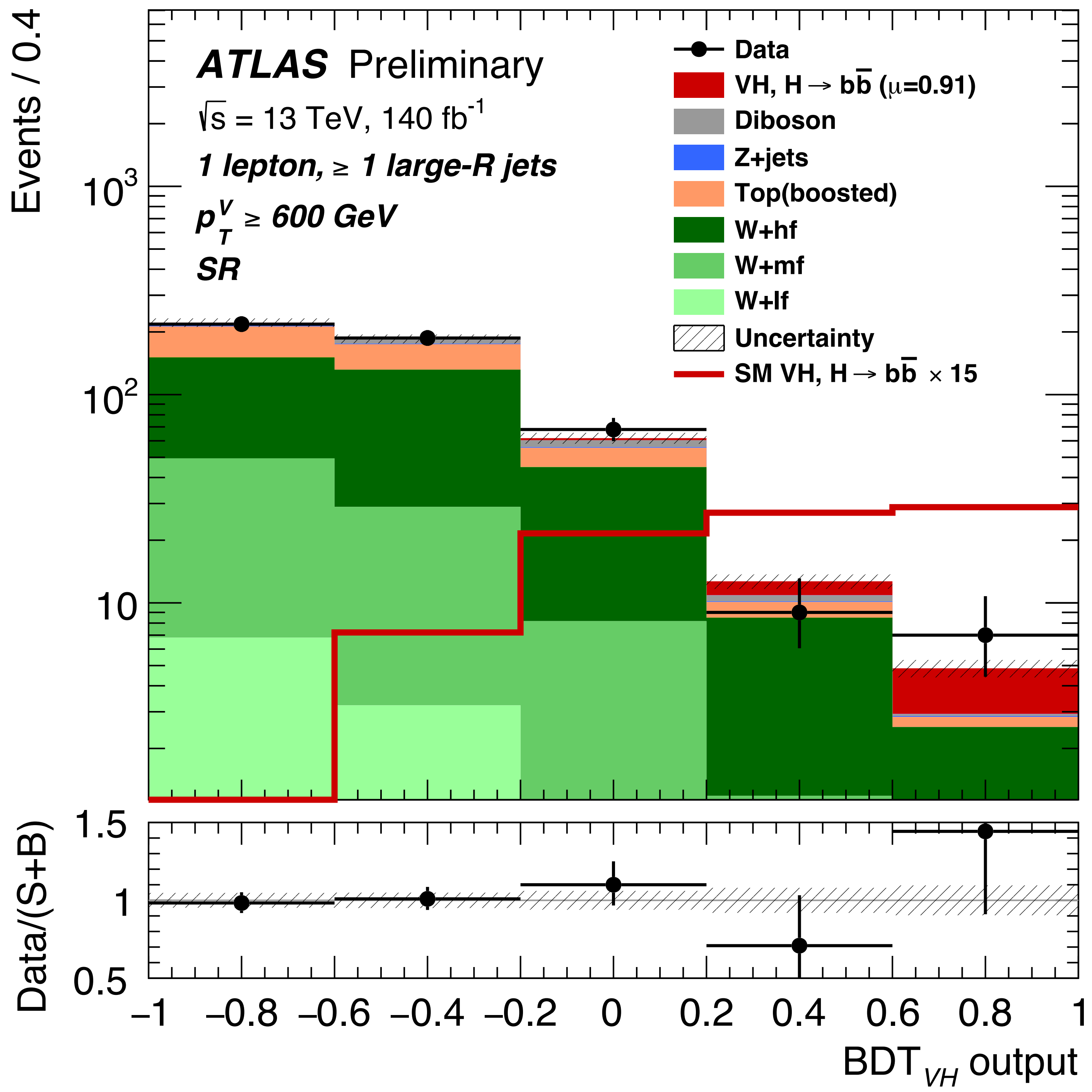


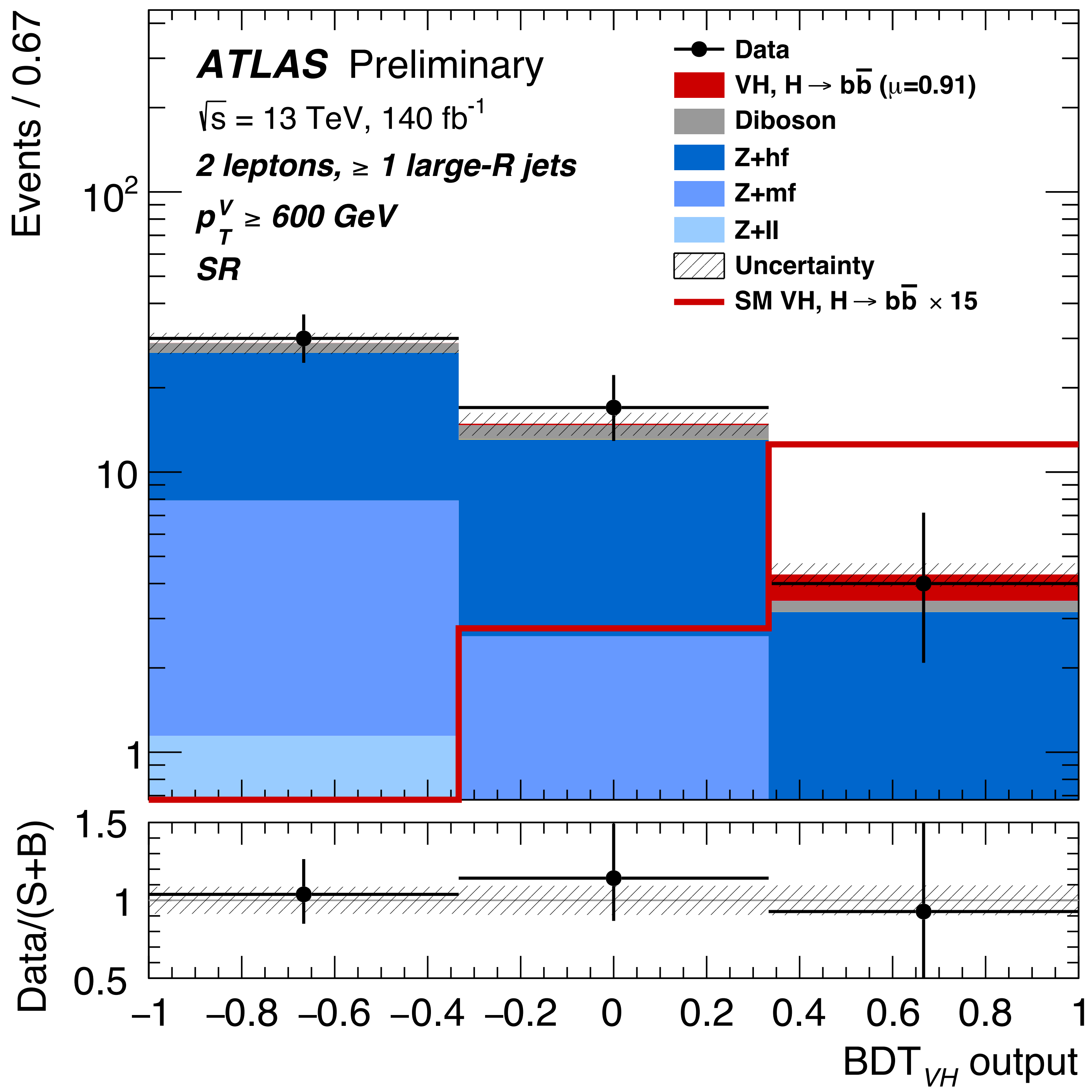
Nikhef

Postfit plots

pTV > 600 GeV

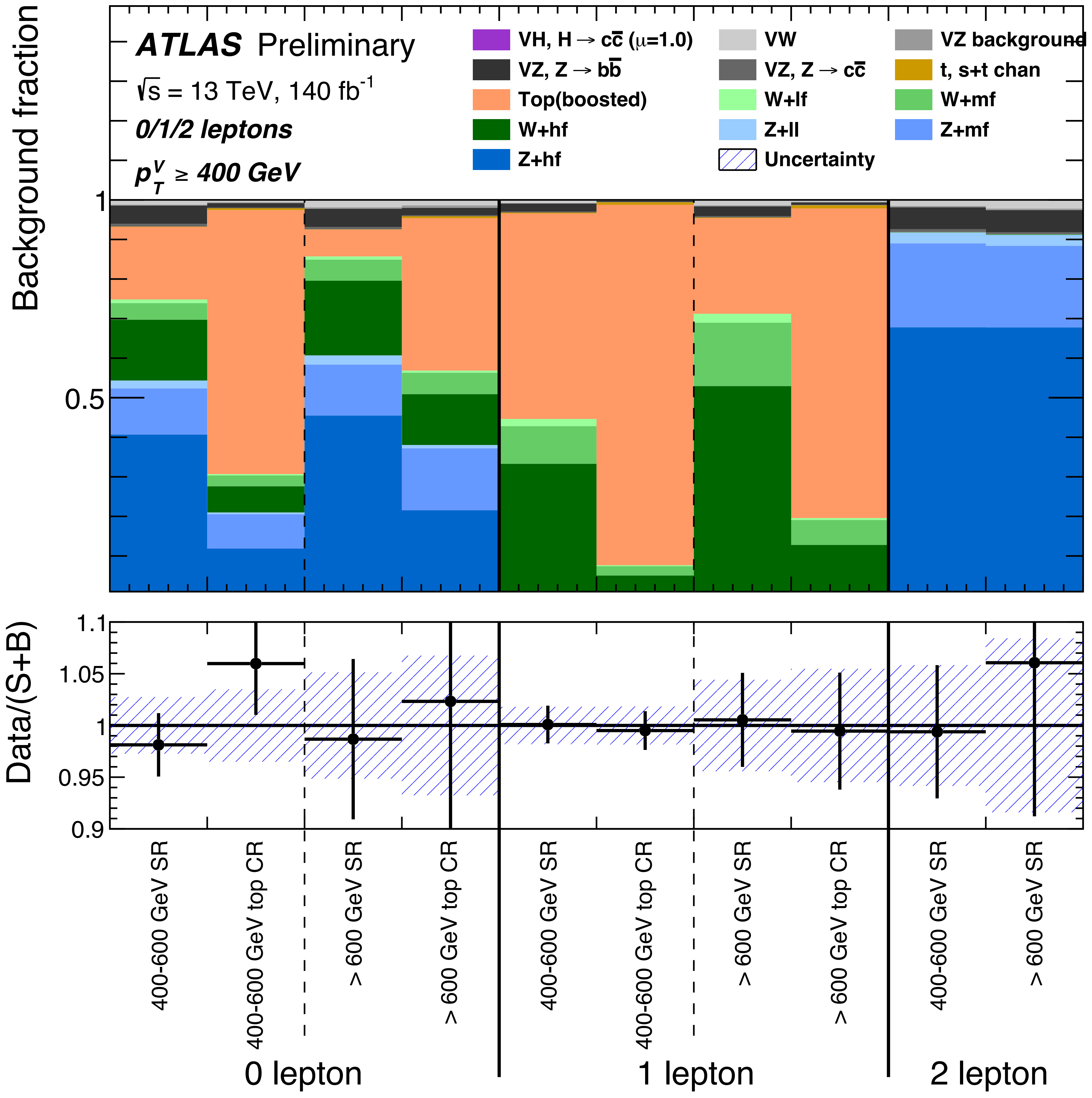






Nikhef

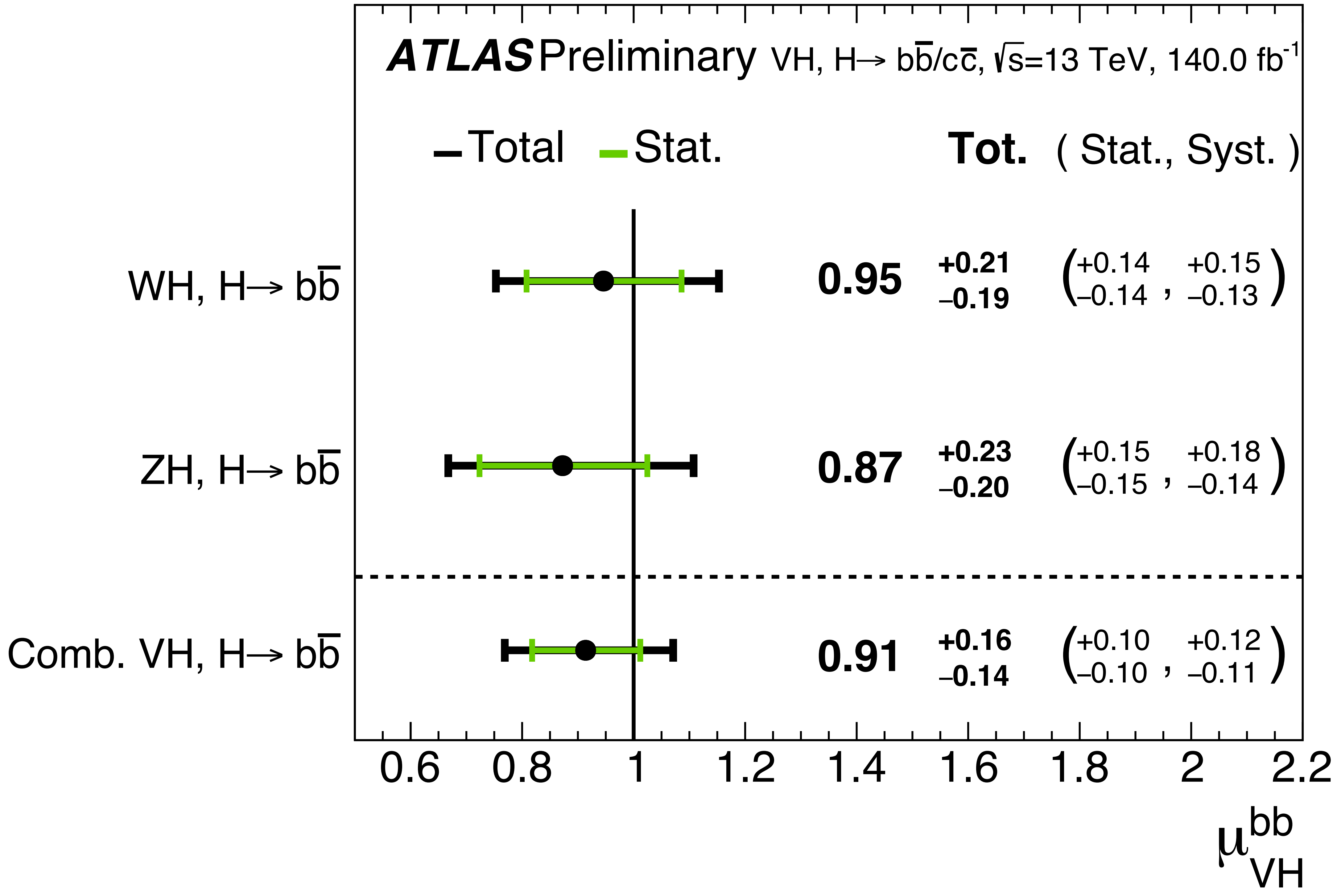
Background composition

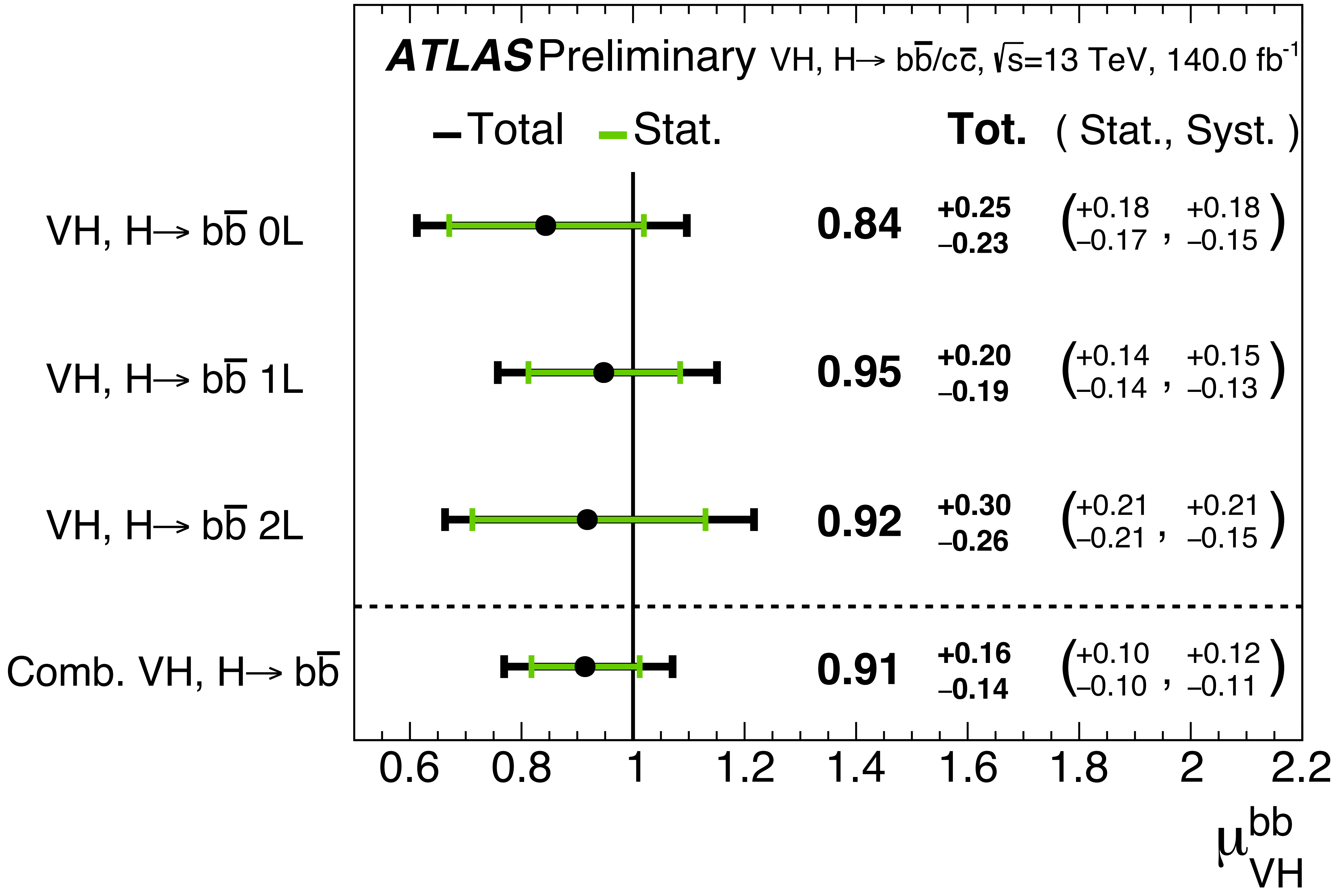


Results - Best fit values and uncertainties

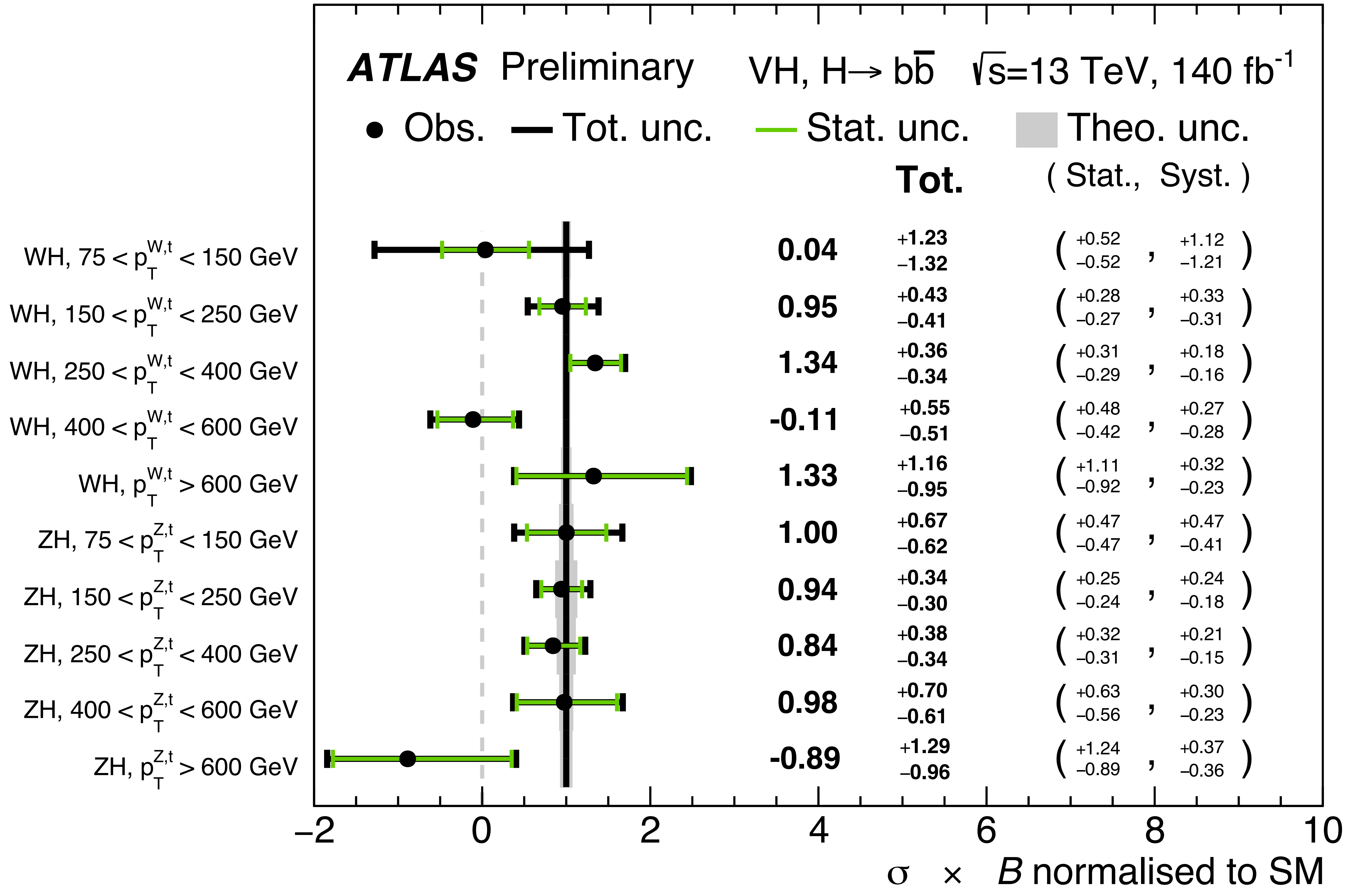
STXS region			SM prediction	Measurement	Stat. unc.	Syst. unc. [fb]		
Process	$p_{\mathrm{T}}^{V,\,\mathrm{t}}$ interval	$N_{\mathrm{jet}}^{\mathrm{t}}$	[fb]	[fb]	[fb]	Th. sig.	Th. bkg.	Exp.
$W(\ell\nu)H$	400–600 GeV	≥0	1.03 ± 0.05	-0.11 ± 0.54	0.46	0.05	0.24	0.09
	> 600 GeV	≥0	0.20 ± 0.01	0.26 ± 0.21	0.20	0.02	0.04	0.03
$Z(\ell\ell/\nu\nu)H$	400–600 GeV	≥0	0.62 ± 0.05	0.60 ± 0.40	0.37	0.07	0.12	0.08
	> 600 GeV	≥0	0.11 ± 0.01	-0.10 ± 0.12	0.12	0.01	0.03	0.01

Results


ATLAS Preliminary VH, H→ bb̄/cc̄, √s=13 TeV, 140.0 fb-1
Total
Stat.
Tot. (Stat., Syst.)
WH, H→ bb̄
0.95 +0.21 −0.19 (+0.14 −0.14 , +0.15 −0.13)
ZH, H→ bb̄
0.87 +0.23 −0.20 (+0.15 −0.15 , +0.18 −0.14)
Comb. VH, H→ bb̄
0.91 +0.16 −0.14 (+0.10 −0.10 , +0.12 −0.11)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
μ bb VH

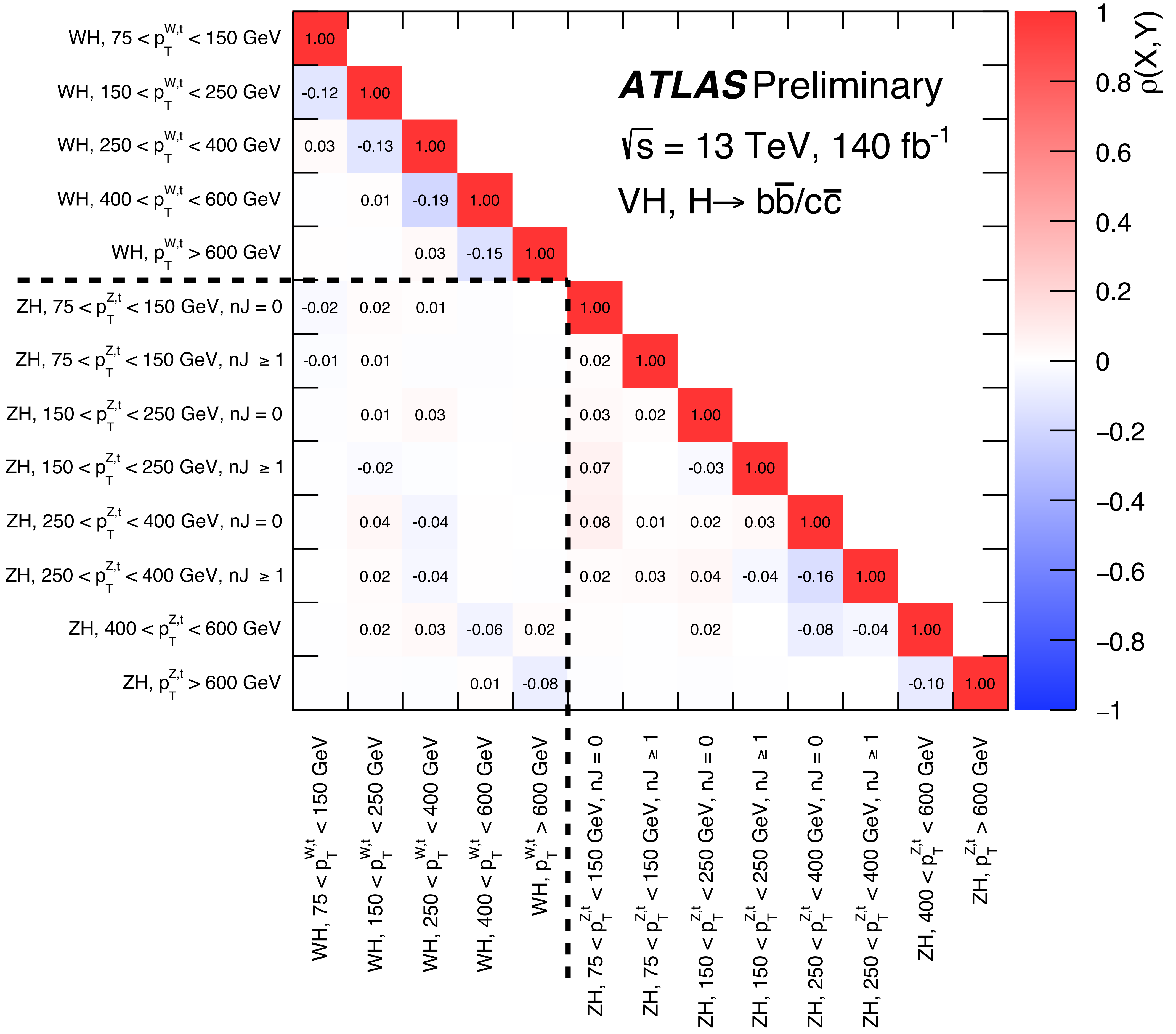

ATLAS Preliminary VH, H→ bb̄/cc̄, √s=13 TeV, 140.0 fb-1
Total
Stat.
Tot. (Stat., Syst.)
VH, H→ bb̄ 0L
0.84 +0.25 −0.23 (+0.18 −0.17 , +0.18 −0.15)
VH, H→ bb̄ 1L
0.95 +0.20 −0.19 (+0.14 −0.14 , +0.15 −0.13)
VH, H→ bb̄ 2L
0.92 +0.30 −0.26 (+0.21 −0.21 , +0.21 −0.15)
Comb. VH, H→ bb̄
0.91 +0.16 −0.14 (+0.10 −0.10 , +0.12 −0.11)
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
μ bb VH

Results



Nikhef

Results - Correlation matrix

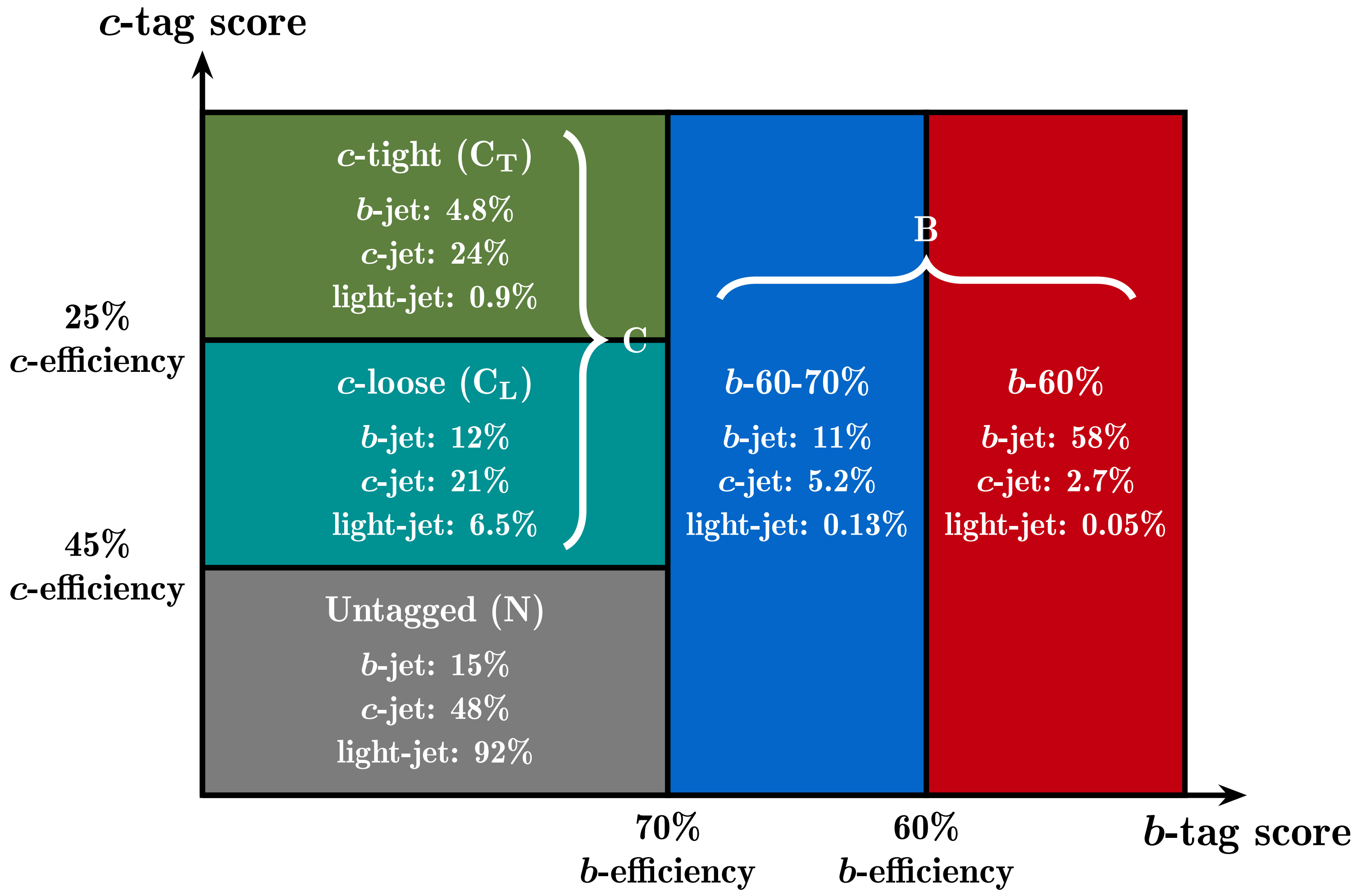


Nikhef

Flavour tagging

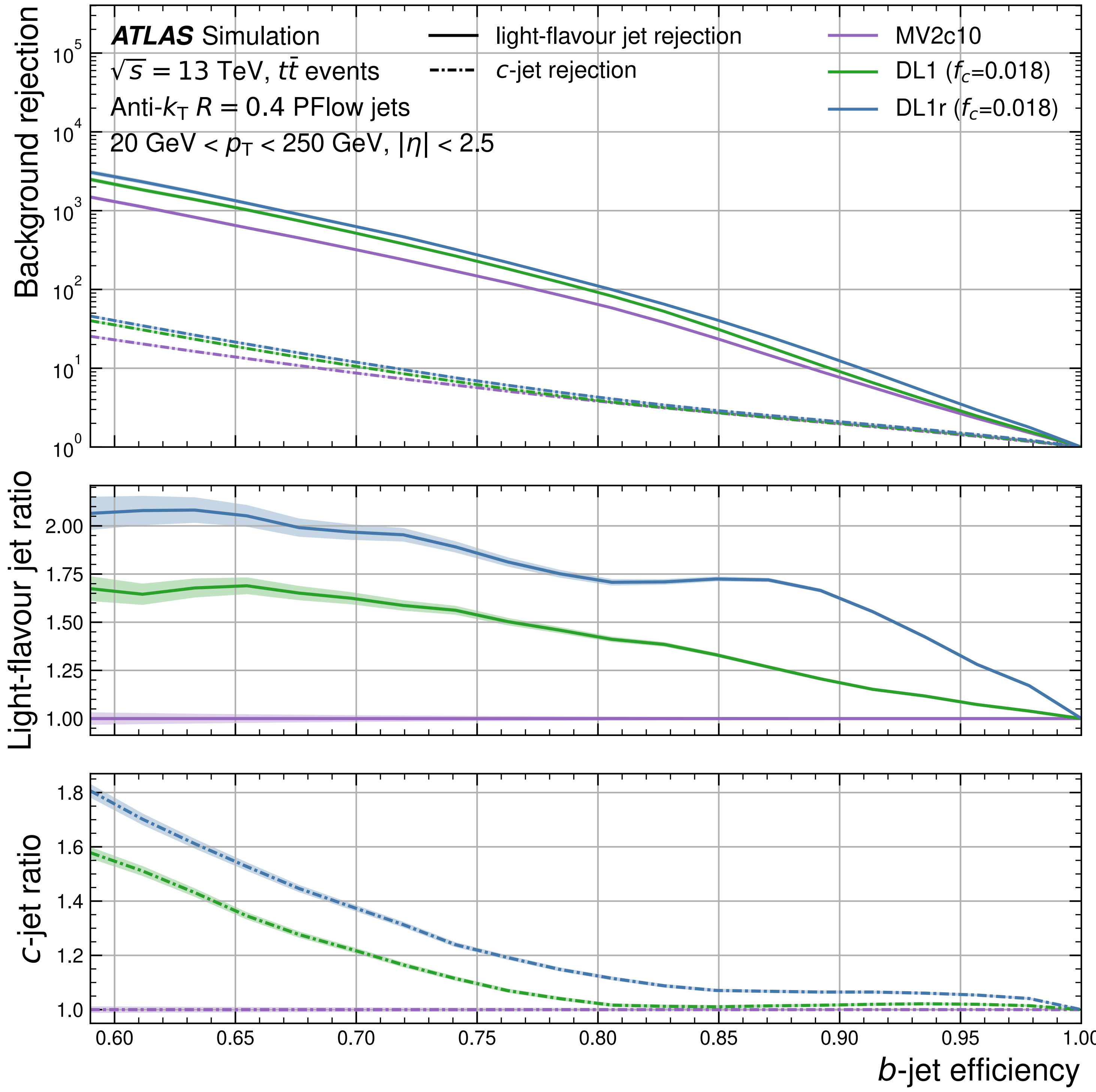
Boosted regime: 70% working point b-tagging

	c-jet rejection	Light-jet rejection
New b-tag	11.9	625
Old b-tag	8	301



Efficiency for jet flavours in the different regions extracted from $t\bar{t}$ MC samples

The light-flavour jet and c-jet rejection factors as a function of εb



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2019-006/

Nikhef