VH,H→bb Measurements in ATLAS

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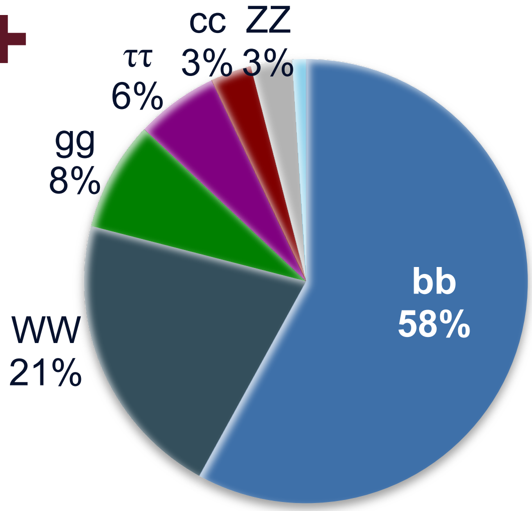
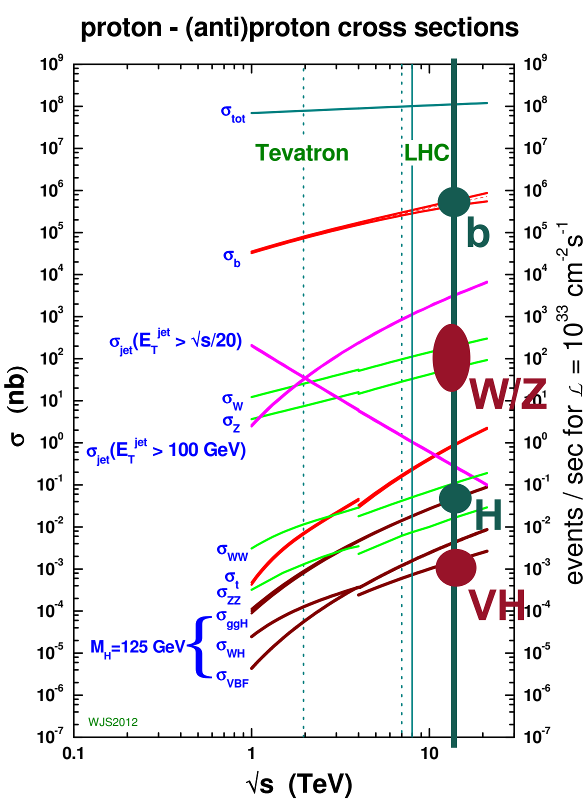
ATLAS EXPERIMENT

UNIVERSITY OF OXFORD

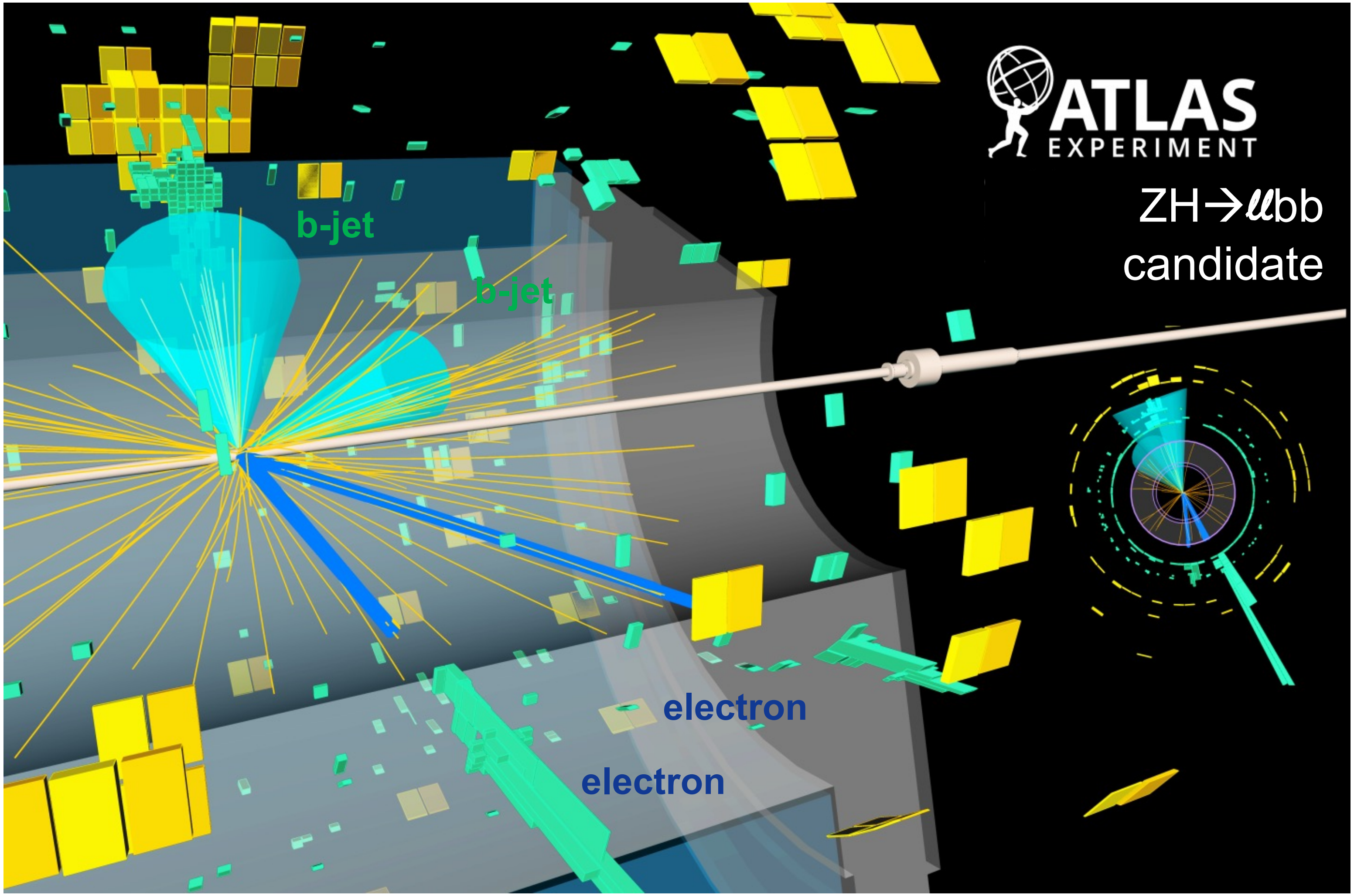
The VH,H→bb Process





- Higgs boson (mass = 125 GeV) decays to bottom quarks account for more than half of all Higgs boson decays!
- However, production of (b-)jet background abundant in pp collisions
- VH production with V→leptons decays
  - Leptons as trigger signature
  - Suppression of multi-jet events
- H→bb decays observed (~7σ in latest VH,H→bb measurement)
  → transition to precise measurements of VH production in H→bb channel

VH,H→bb Candidate Events



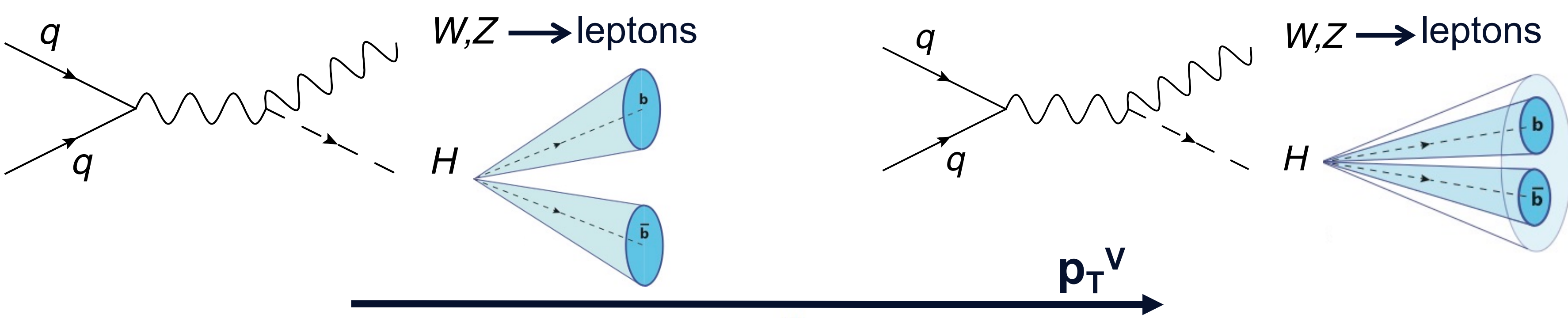
V and H "back-to-back" → p_T^V (~good experimental resolution) as proxy for p_T^H (~bad experimental resolution)

VH, H→bb Signatures

3 V boson decay channels targeted:

ZH→ννbb (“0-lepton”), WH→ℓνbb (“1-lepton”), ZH→ℓℓbb (“2-lepton”)

Jargon Alert: “Lepton” = lepton directly visible in detector = muon or electron



$$\Delta R(b_1, b_2) \approx \frac{2 \cdot m_H}{p_T^H}$$

2 **resolved** jets
(radius R=0.4)

jets **merge** → 1 large jet
(R=1.0) with substructure

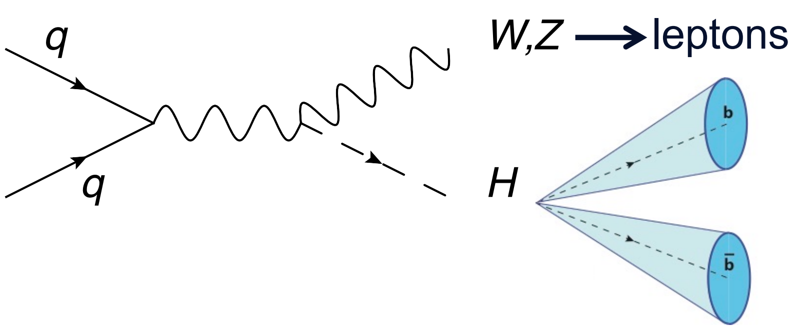
Recently ATLAS performed the **first combination of resolved VH,H→bb and boosted VH,H→bb** measurements! (ATLAS-CONF-2021-051)

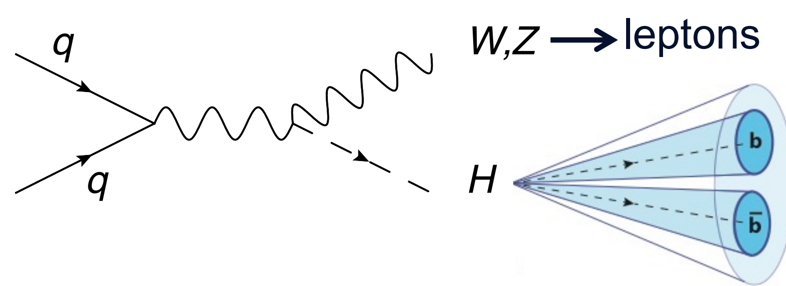
Event Selection

ZH→$\nu\nu$bb
0 electrons or muons
large amount of E^T_{miss}

WH→$\ell\nu$bb
1 electron or muon

ZH→$\ell\ell$bb
2 electrons or muons
$m_{\ell\ell}$ consistent with m_Z





0/1-lepton: **p_T^V > 150 GeV**
2-lepton: **p_T^V > 75 GeV**

Exactly **2 b-tagged R=0.4 jets**
(more non-b-jets allowed)

0/1/2-lepton: **p_T^V > 250 GeV**

≥1 R=1.0 jet
(highest p_T jet = H candidate)
Inside large-R jet: reconstruct small
track-based jets for b-tagging

+ more requirements for multijet suppression in 0 lepton and background suppression in boosted analysis

Combination Strategy

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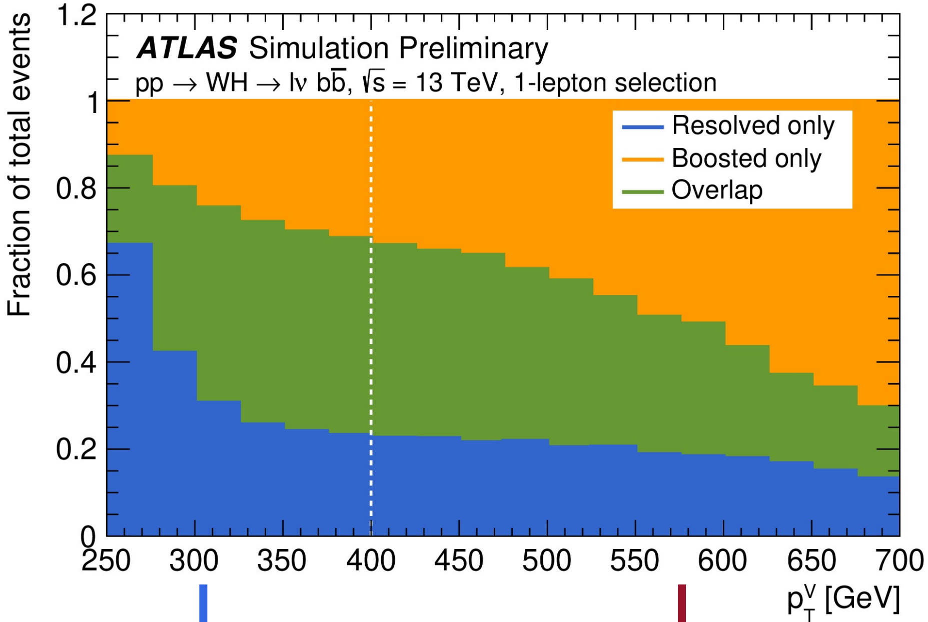


p_T^V < 400 GeV
Resolved only
(blue+green)

p_T^V > 400 GeV
Boosted only
(yellow+green)

- Combination based on two stand-alone VH,H→bb results:
  - Resolved*: Eur. Phys. J. C 81 (2021) 178
  - Boosted*: Phys. Lett. B 816 (2021) 136204
  - → **Significant overlap of analysis phase spaces**
  - → Switch between resolved and boosted at p_T^V = 400 GeV
- General analysis strategies (selection, control regions, discriminant) unchanged
- Slight adjustments in treatment of background normalisations (determined from data) and systematic uncertainties

*full ATLAS Run-2 data set used (139 fb^{-1})

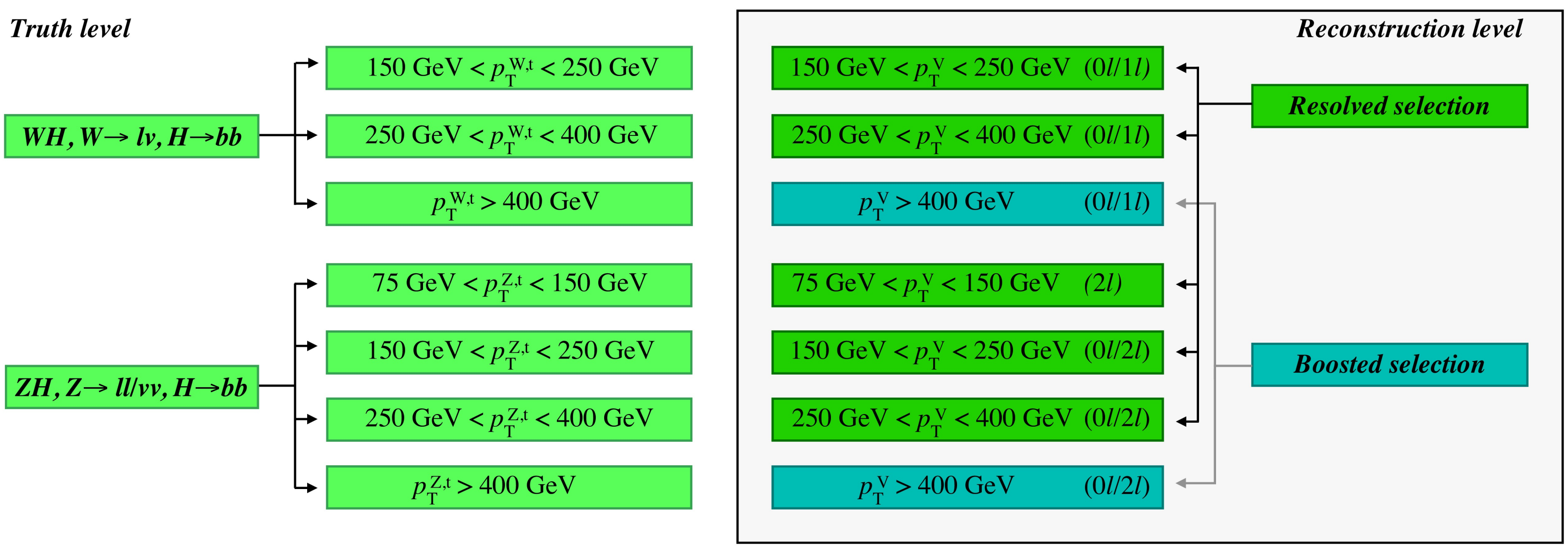
Measurement Categories

- **3 p_T^V categories in 0/1-lepton and 4 p_T^V categories in 2-lepton**

→ Main measurement aim: extract WH and ZH cross section as a function of p_T^V as defined by the STXS framework (templates of x-sec based on bins in p_T^V on particle (“truth”) level)

- Split by jet multiplicity to define high S/B and low S/B categories

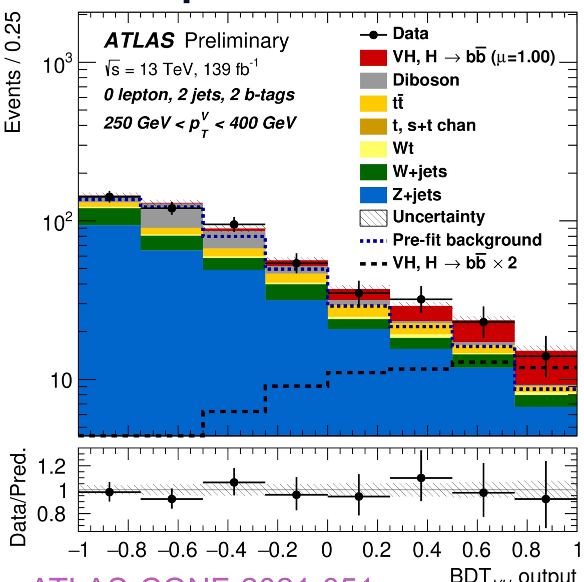
- Dedicated control regions to constrain main backgrounds



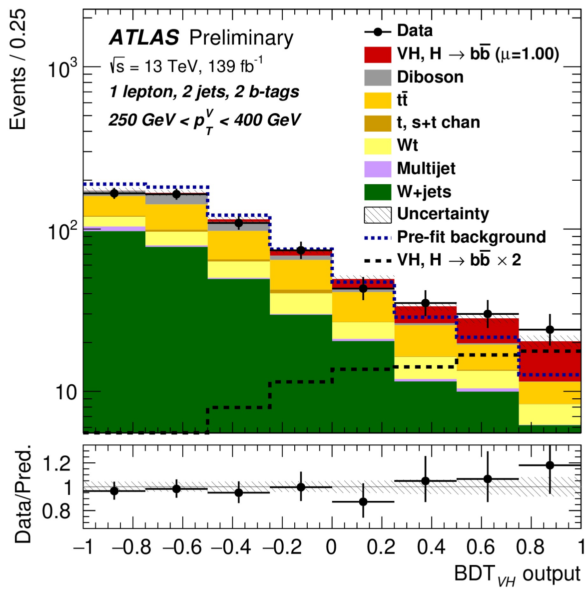
Resolved Analysis Discriminant Distributions (Selection)

Multivariant discriminant (based on BDTs) for enhanced signal-background separation

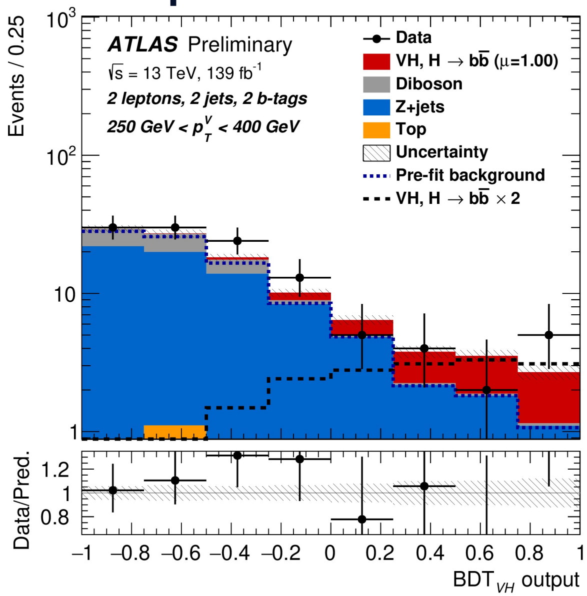
0-lepton



1-lepton



2-lepton



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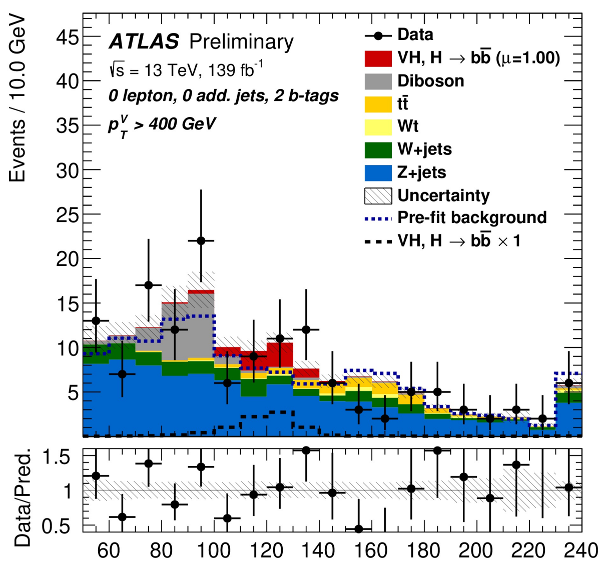
Main backgrounds: **$Z(\nu\nu/\ell\ell)$+jets**, **$W(\ell\nu)$+jets**, **top quark pairs (tt)**

Sub-leading backgrounds: single top quarks (Wt, t), V boson pairs (diboson), multi-jets

Boosted Analysis Discriminant Distributions (Selection)

Invariant mass of the highest p_T large-R jet (=Higgs candidate jet)

0-lepton



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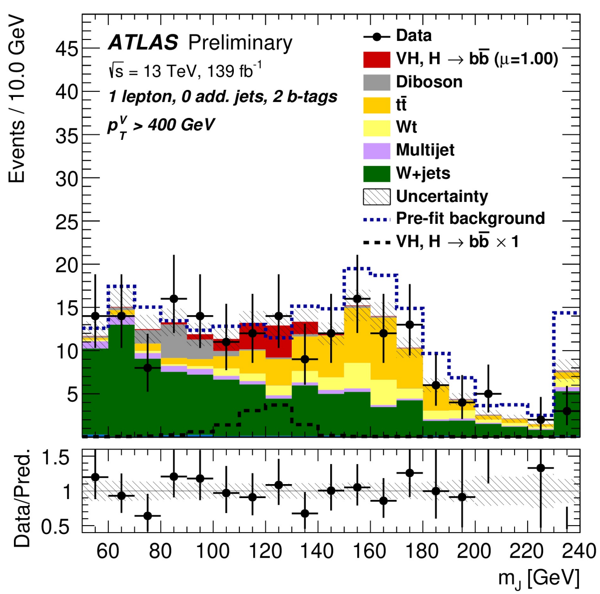
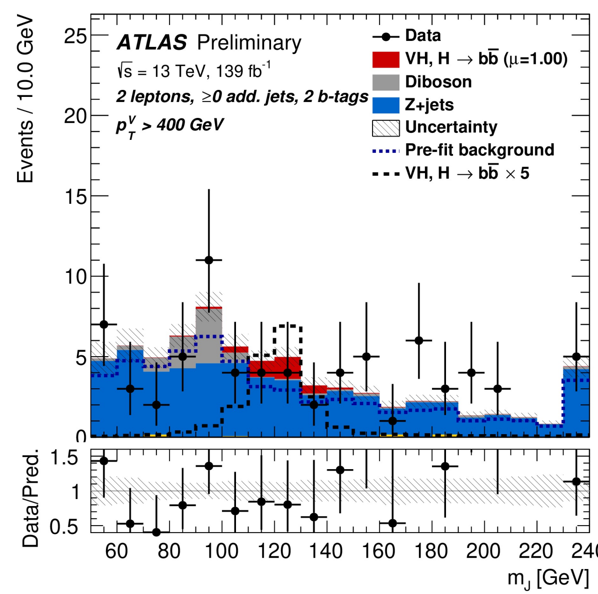
1-lepton



2-lepton



Main backgrounds: **Z(νν/ℓℓ)+jets**, **W(ℓν)+jets**, **top quark pairs (tt)**

Sub-leading backgrounds: single top quarks (Wt, t), V boson pairs (diboson), multi-jets

Results

Compatible with SM

WH/ZH signal strengths (μ = observed/expected number of signal events):

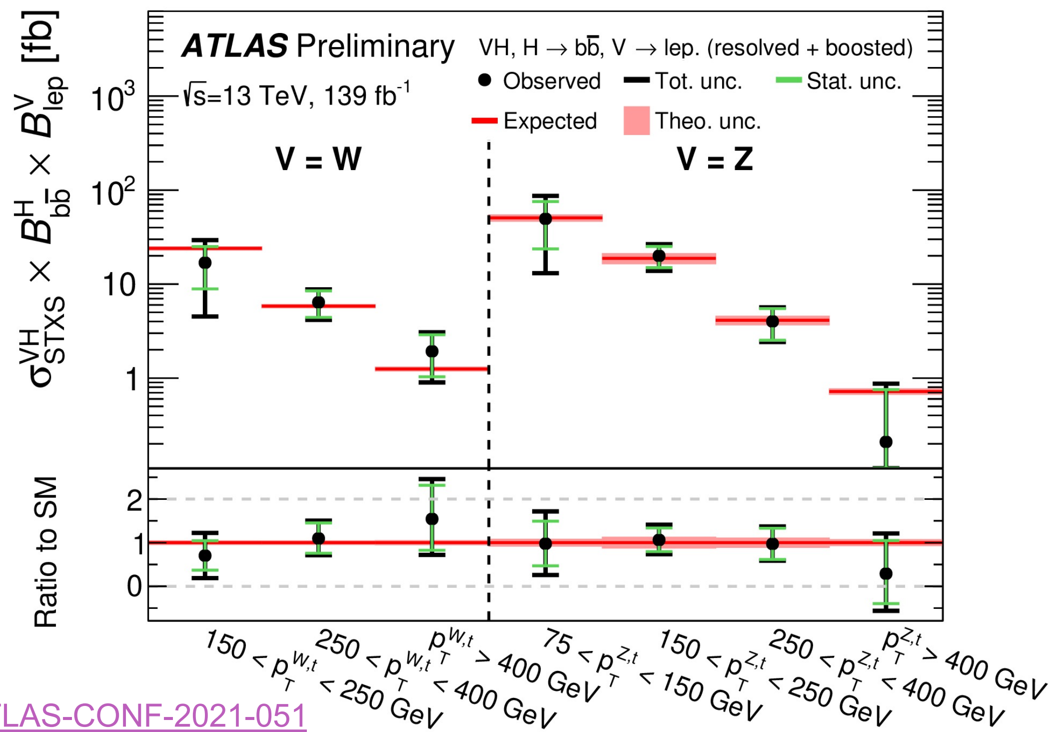
$$\mu^{bb}_{WH} = 1.03^{+0.28}_{-0.27} = 1.03 \pm 0.19\ (\text{stat.})^{+0.21}_{-0.19}\ (\text{syst.})$$

$$\mu^{bb}_{ZH} = 0.97^{+0.25}_{-0.23} = 0.97 \pm 0.17\ (\text{stat.})^{+0.18}_{-0.15}\ (\text{syst.})$$

Most precise VH STXS measurement to date!

STXS measurements statistically limited (but for p_T^V<250 GeV contribution from systematic uncertainties of comparable size)

Largest sources of uncertainties: modelling of MC backgrounds, b-tagging, large-R jet calibration



Beyond Standard Model Interpretation: Anomalous Couplings

Consider anomalous VH,H→bb couplings in an extension of the SM Lagrangian (SMEFT approach):

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{\boxed{d}} \frac{1}{\boxed{\Lambda}^{d-4}} \left(\sum_i \boxed{c_i^{(d)}} \boxed{O_i^{(d)}} \right)$$

Dimension
(consider up to d=6)

Scale of new physics
(set to 1 TeV)

Coupling modifiers
(c_i=0 in SM)

Dimension d
operators

- 14 operators affect ZH,H→bb and 7 affect WH,H→bb
  - **Aim:** benchmark VH,H→bb combination by setting limits on 3 coupling modifiers with large p_T^V dependence

EFT Interpretation Results

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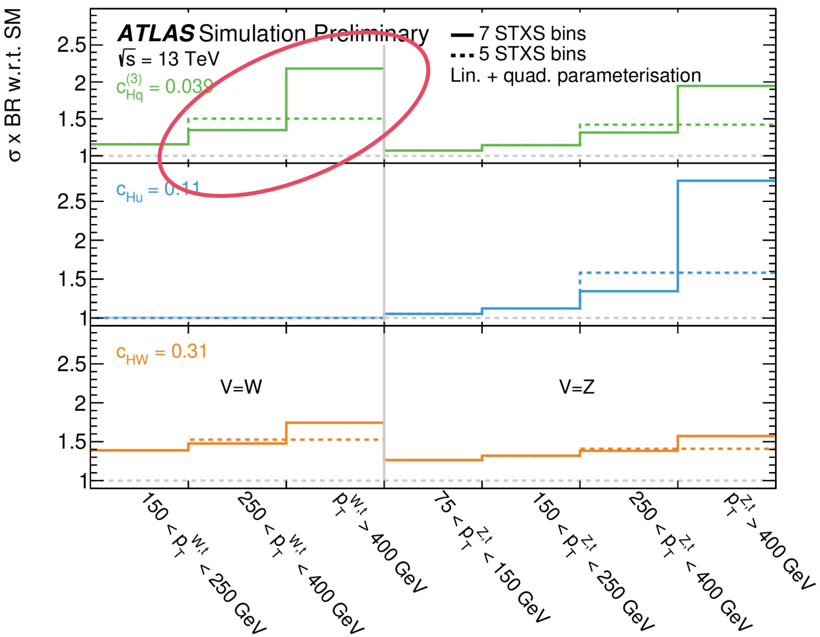
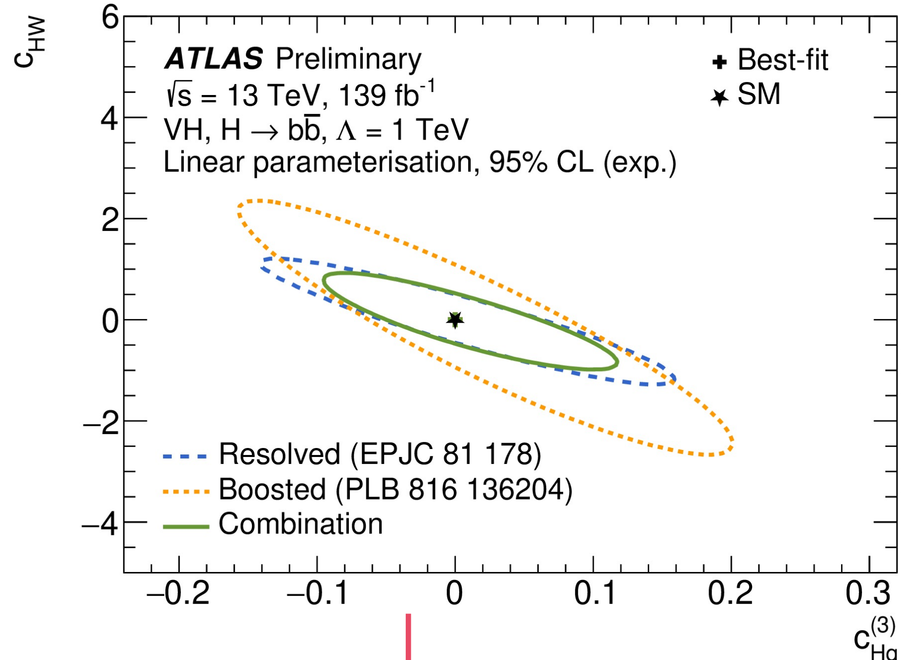




Impact of EFT modifiers on STXS cross sections:

Large impact at high p_T^V
→ dedicated high p_T^V analysis categories provide additional constraining power

VH,H→bb combination improves on EFT limits of stand-alone analyses!

Summary

- VH,H→bb channel offers unique opportunity to measure VH production with good precision and reach high p_T which is particularly sensitive to beyond SM effects
- First combination of VH,H→bb measurements to measure WH and ZH cross section as function of p_T^V:
  - "Resolved": two well separated b-jets from Higgs boson decay → high precision
  - "Boosted": b-jets from Higgs boson decay merged in single large jet → extending reach at high p_T^V
- **Most precise WH and ZH STXS measurements to date**
- **Improved limits on EFT coupling modifiers** compared to stand-alone analyses
- All measurements in good agreement with SM

Backup

+ Detailed Selection (Resolved)

Selection	0-lepton	1-lepton, e sub-channel	1-lepton, μ sub-channel	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons	Exactly 1 *tight* electron 0 additional *loose* leptons $p_{\mathrm{T}} > 27$ GeV	Exactly 1 *tight* muon 0 additional *loose* leptons $p_{\mathrm{T}} > 25$ GeV	Exactly 2 *loose* leptons $p_{\mathrm{T}} > 27$ GeV Same-flavour Opposite-sign charges ($\mu\mu$)
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–	–	81 GeV $< m_{\ell\ell} <$ 101 GeV
Jet p_{T}	> 20 GeV for $\|\eta\| < 2.5$ > 30 GeV for $2.5 < \|\eta\| < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
Jet categories	Exactly 2 / Exactly 3 jets	Exactly 2 / Exactly 3 jets		Exactly 2 / ≥ 3 jets
H_{T}	> 120 GeV (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b_1}, \vec{b_2})$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–		–
p_{T}^{V} regions	– 150 GeV $< p_{\mathrm{T}}^{V} <$ 250 GeV $p_{\mathrm{T}}^{V} > 250$ GeV	– 150 GeV $< p_{\mathrm{T}}^{V} <$ 250 GeV $p_{\mathrm{T}}^{V} > 250$ GeV		75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV 150 GeV $< p_{\mathrm{T}}^{V} <$ 250 GeV $p_{\mathrm{T}}^{V} > 250$ GeV
Signal regions	$\Delta R(\vec{b_1}, \vec{b_2})$ signal selection			
Control regions	High and low $\Delta R(\vec{b_1}, \vec{b_2})$ side-bands			

Detailed Selection (Boosted)

HIGG-2018-52

Selection	0 lepton channel	1 lepton channel: e sub-channel	1 lepton channel: μ sub-channel	2 leptons channel: e sub-channel	2 leptons channel: μ sub-channel
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single electron	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single electron	$E_{\mathrm{T}}^{\mathrm{miss}}$
Leptons	0 *baseline* leptons	1 *signal* lepton $p_{\mathrm{T}} > 27$ GeV no second *baseline* lepton	1 *signal* lepton $p_{\mathrm{T}} > 25$ GeV no second *baseline* lepton	2 *baseline* leptons among which ≥ 1 *signal* lepton, $p_{\mathrm{T}} > 27$ GeV both leptons of the same flavour -	2 *baseline* leptons among which ≥ 1 *signal* lepton, $p_{\mathrm{T}} > 27$ GeV both leptons of the same flavour opposite sign muons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250GeV	> 50 GeV	-	-	
p_{T}^{V}	$p_{\mathrm{T}}^{V} > 250$ GeV				
Large-R jets	at least one large-R jet, $p_{\mathrm{T}} > 250$ GeV, $\lvert\eta\rvert < 2.0$				
Track-jets	at least two track-jets, $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.5$, associated to the leading large-R jet				
b-jets	leading two track-jets associated to the leading large-R must be b-tagged (MV2c10, 70%)				
m_{J}	> 50 GeV				
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R \text{ jets})]$	$> 30°$	-			
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, H_{\mathrm{cand}})$	$> 120°$	-			
$\Delta\phi\ (\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,\ trk}}^{\mathrm{miss}})$	$< 90°$	-			
$\Delta y(V, H_{\mathrm{cand}})$	-	$\lvert\Delta y(V, H_{\mathrm{cand}})\rvert < 1.4$			
$m_{\ell\ell}$	-			66 GeV $< m_{\ell\ell} <$ 116 GeV	
Lepton p_{T} imbalance	-			$(p_{\mathrm{T}}^{\ell_1} - p_{\mathrm{T}}^{\ell_2})/p_{\mathrm{T}}^{Z} < 0.8$	

Resolved MVA Set-up

Variable	0-lepton	1-lepton	2-lepton
m_{bb}	×	×	×
$\Delta R(\vec{b_1}, \vec{b_2})$	×	×	×
$p_{\mathrm{T}}^{b_1}$	×	×	×
$p_{\mathrm{T}}^{b_2}$	×	×	×
p_{T}^{V}	$\equiv E_{\mathrm{T}}^{\mathrm{miss}}$	×	×
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\mathrm{MV2}(b_1)$	×	×	
$\mathrm{MV2}(b_2)$	×	×	
$\lvert\Delta\eta(\vec{b_1}, \vec{b_2})\rvert$	×		
m_{eff}	×		
$p_{\mathrm{T}}^{\mathrm{miss,st}}$	×		
$E_{\mathrm{T}}^{\mathrm{miss}}$	×	×	
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_{T}^{W}		×	
$\lvert\Delta y(\vec{V}, \vec{bb})\rvert$		×	
m_{top}		×	
$\lvert\Delta\eta(\vec{V}, \vec{bb})\rvert$			×
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{S_{\mathrm{T}}}$			×
$m_{\ell\ell}$			×
$\cos\theta(\vec{\ell^-}, \vec{Z})$			×
	Only in 3-jet events		
$p_{\mathrm{T}}^{\mathrm{jet}_3}$	×	×	×
m_{bbj}	×	×	×

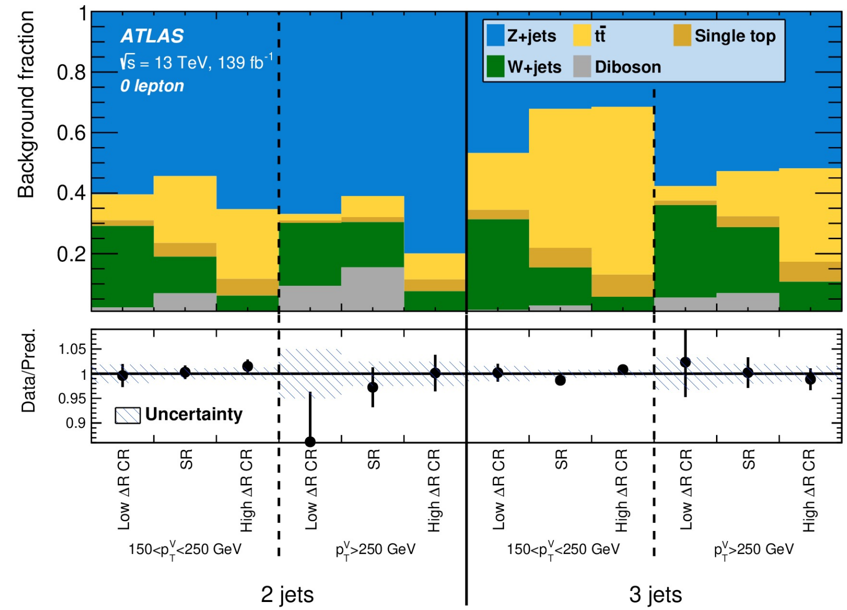
Boosted decision trees (as provided by TMVA framwork) used as machine learning algorithm

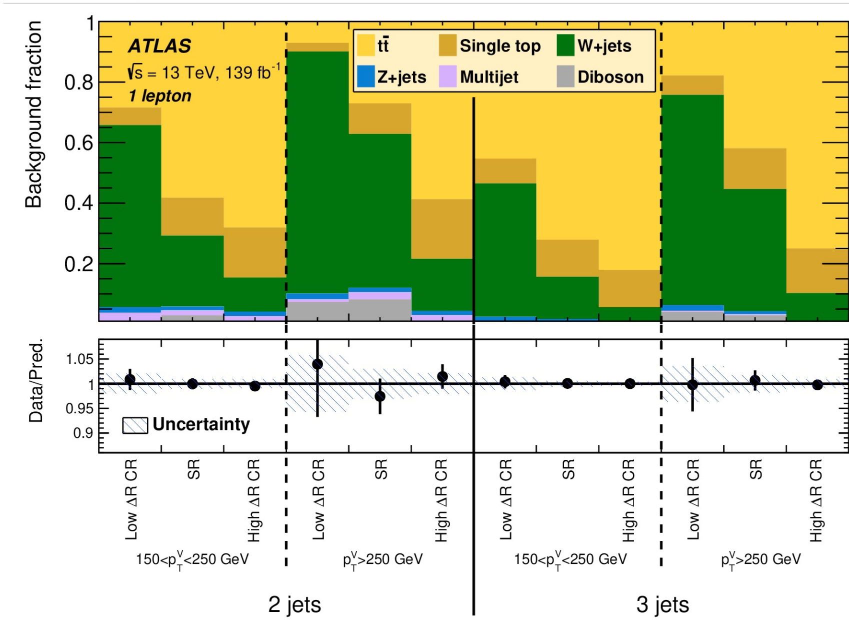
+ Analysis Regions (Resolved)

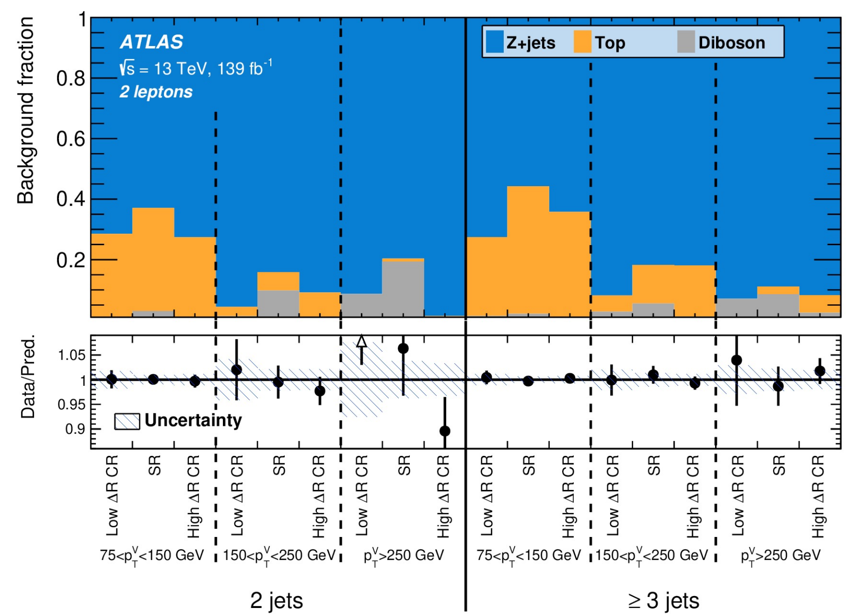
From stand-alone analysis!

Channel	Region	$75\text{ GeV} < p_T^V < 150\text{ GeV}$		$150\text{ GeV} < p_T^V < 250\text{ GeV}$		$p_T^V > 250\text{ GeV}$	
		2-jets	3-jets	2-jets	3-jets	2-jets	3-jets
0-lepton	Low-ΔR-CR	–	–	Yields	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High-ΔR-CR	–	–	Yield	Yield	Yield	Yield
1-lepton	Low-ΔR-CR	–	–	Yield	Yield	Yield	Yield
	Signal region	–	–	BDT	BDT	BDT	BDT
	High-ΔR-CR	–	–	Yield	Yield	Yield	Yield
2-lepton	Low-ΔR-CR	Yield	Yield	Yield	Yield	Yield	Yield
	Signal region	BDT	BDT	BDT	BDT	BDT	BDT
	High-ΔR-CR	Yield	Yield	Yield	Yield	Yield	Yield

(The column headers above sit under a spanning header "Categories".)







Analysis Regions (Merged)

From stand-alone analysis!

<table>
<tr><th rowspan="4">Channel</th><th colspan="6">Categories</th></tr>
<tr><th colspan="3">$250 < p_{\mathrm{T}}^{V} < 400$ GeV</th><th colspan="3">$p_{\mathrm{T}}^{V} \geq 400$ GeV</th></tr>
<tr><th colspan="2">0 add. b-track-jets</th><th rowspan="2">≥ 1 add. b-track-jets</th><th colspan="2">0 add. b-track-jets</th><th rowspan="2">≥ 1 add. b-track-jets</th></tr>
<tr><th>0 add. small-R jets</th><th>≥ 1 add. small-R jets</th><th>0 add. small-R jets</th><th>≥ 1 add. small-R jets</th></tr>
<tr><td>0-lepton</td><td>HP SR</td><td>LP SR</td><td>CR</td><td>HP SR</td><td>LP SR</td><td>CR</td></tr>
<tr><td>1-lepton</td><td>HP SR</td><td>LP SR</td><td>CR</td><td>HP SR</td><td>LP SR</td><td>CR</td></tr>
<tr><td>2-lepton</td><td colspan="3">SR</td><td colspan="3">SR</td></tr>
</table>

Background Normalisations

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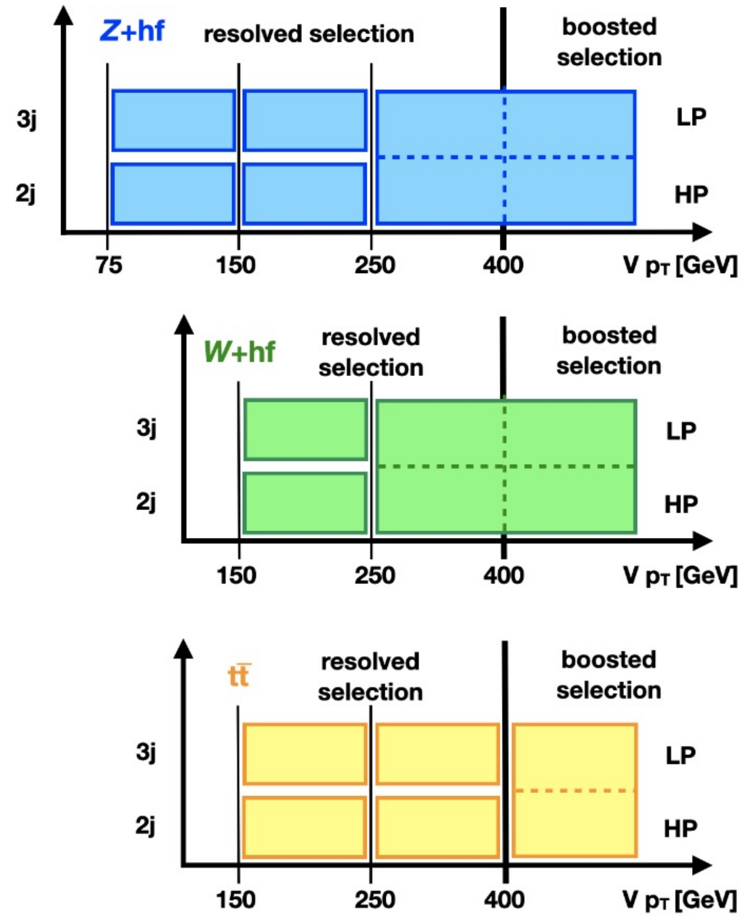
Background normalization factors (determined from data)
→ Adjusted for combination
→ Additional acceptance uncertainties across dashed lines

Process and category	Normalisation factor
$t\bar{t}$ 2-jet, 150 GeV $< p_T^V <$ 250 GeV	0.97 ± 0.09
$t\bar{t}$ 3-jet, 150 GeV $< p_T^V <$ 250 GeV	0.92 ± 0.06
$t\bar{t}$ 2-jet, 250 GeV $< p_T^V <$ 400 GeV	0.97 ± 0.14
$t\bar{t}$ 3-jet, 250 GeV $< p_T^V <$ 400 GeV	0.83 ± 0.08
$t\bar{t}$ $p_T^V >$ 400 GeV	0.79 ± 0.12
W+hf 2-jet, 150 GeV $< p_T^V <$ 250 GeV	1.11 ± 0.12
W+hf 3-jet, 150 GeV $< p_T^V <$ 250 GeV	1.16 ± 0.10
W+hf $p_T^V >$ 250 GeV	1.10 ± 0.10
Z+hf 2-jet, 75 GeV $< p_T^V <$ 150 GeV	1.28 ± 0.08
Z+hf 3-jet, 75 GeV $< p_T^V <$ 150 GeV	1.17 ± 0.05
Z+hf 2-jet, 150 GeV $< p_T^V <$ 250 GeV	1.19 ± 0.07
Z+hf 3-jet, 150 GeV $< p_T^V <$ 250 GeV	1.11 ± 0.05
Z+hf $p_T^V >$ 250 GeV	1.07 ± 0.05



STXS Results Compared with Stand-Alone Analyses

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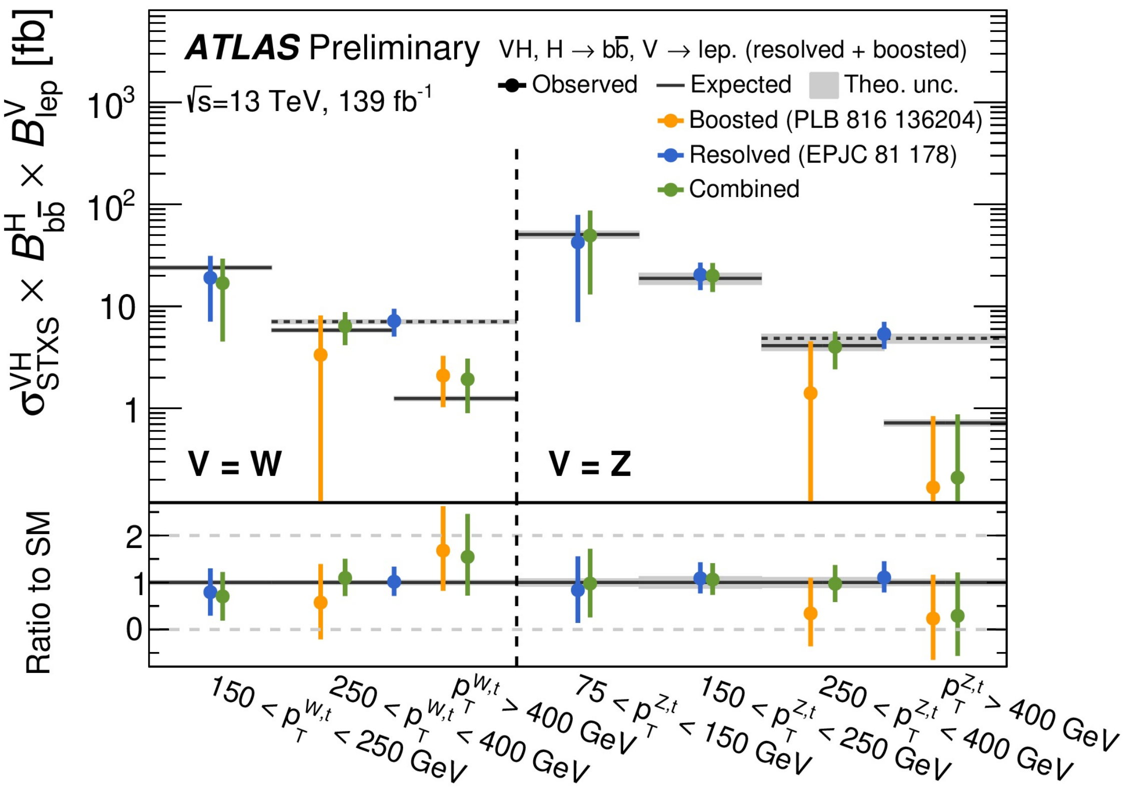

STXS: Impact of Uncertainties

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Category	WH, 150–250 GeV	WH, 250–400 GeV	WH, > 400 GeV	ZH, 75–150 GeV	ZH, 150–250 GeV	ZH, 250–400 GeV	ZH, > 400 GeV
Total	73%	36%	56%	75%	32%	40%	305%
Statistical	48%	32%	48%	52%	26%	37%	248%
Systematic	56%	17%	29%	53%	19%	16%	177%
Statistical uncertainties							
Data stat only	44%	29%	45%	44%	23%	34%	242%
Floating normalisations	26%	9%	14%	21%	11%	10%	57%
$t\bar{t}$ $e\mu$ control region	4%	≤1%	≤1%	23%	4%	8%	3%
Experimental uncertainties							
Total experimental	34%	9%	14%	42%	11%	7%	95%
↪ lepton	4%	2%	3%	3%	≤1%	≤1%	4%
↪ $E_{\mathrm{T}}^{\mathrm{miss}}$	24%	≤1%	≤1%	25%	3%	≤1%	9%
↪ Small-R jets	17%	6%	6%	28%	7%	4%	19%
↪ Large-R jets	≤1%	≤1%	9%	≤1%	≤1%	≤1%	89%
↪ Calo b-tagging (b-jets)	8%	2%	≤1%	18%	8%	5%	6%
↪ Calo b-tagging (c-jets)	14%	6%	≤1%	2%	2%	≤1%	3%
↪ Calo b-tagging (light-flavour jets)	≤1%	≤1%	≤1%	≤1%	≤1%	2%	2%
↪ Calo b-tagging (extrap. from charm)	≤1%	≤1%	≤1%	≤1%	≤1%	≤1%	≤1%
↪ VR b-tagging (b-jets)	≤1%	≤1%	7%	≤1%	≤1%	≤1%	15%
↪ VR b-tagging (c-jets)	≤1%	≤1%	2%	≤1%	≤1%	≤1%	8%
↪ VR b-tagging (light-flavour jets)	≤1%	≤1%	≤1%	≤1%	≤1%	≤1%	21%
↪ VR b-tagging (extrap. from charm)	≤1%	≤1%	≤1%	≤1%	≤1%	≤1%	3%
↪ Pile-up	2%	≤1%	≤1%	5%	≤1%	≤1%	≤1%
↪ Luminosity	2%	2%	2%	≤1%	≤1%	≤1%	5%
Theoretical and modelling uncertainties							
Signal	5%	5%	9%	13%	9%	9%	23%
Backgrounds	43%	13%	23%	37%	12%	11%	145%
↪ single top	17%	8%	8%	5%	≤1%	2%	4%
↪ $t\bar{t}$	22%	3%	9%	10%	4%	3%	13%
↪ W+jets	25%	6%	8%	2%	≤1%	≤1%	14%
↪ Z+jets	7%	2%	5%	29%	9%	6%	115%
↪ Diboson	6%	3%	3%	9%	4%	4%	27%
↪ Multi-jet	≤1%	≤1%	3%	≤1%	≤1%	≤1%	3%
↪ MC statistical	17%	8%	13%	17%	6%	7%	77%

Detailed EFT Interpretation Results

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Wilson coefficient	combination		resolved		boosted	
	linear	linear + quadratic	linear	linear + quadratic	linear	linear + quadratic
68% CL						
$c_{Hq}^{(3)}$	[-0.017, 0.024]	[-0.020, 0.022]	[-0.017, 0.029]	[-0.018, 0.026]	[-0.031, 0.024]	[-0.14, -0.084] $\cup$ [-0.020, 0.0060]
c_{Hu}	[-0.20, 0.070]	[-0.10, 0.046]	[-0.081, 0.22]	[-0.19, 0.10]	[-0.34, 0.0094]	[-0.1, 0.043]
c_{HW}	[-0.19, 0.20]	[-0.32, 0.17]	[-0.17, 0.21]	[-0.24, 0.18]	[-0.56, 0.22]	[-0.68, 0.12]
95% CL						
$c_{Hq}^{(3)}$	[-0.035, 0.047]	[-0.051, 0.039]	[-0.037, 0.053]	[-0.23, -0.18] $\cup$ [-0.047, 0.044]	[-0.055, 0.055]	[-0.16, 0.038]
c_{Hu}	[-0.33, 0.22]	[-0.15, 0.092]	[-0.22, 0.38]	[-0.24, 0.15]	[-0.51, 0.21]	[-0.15, 0.097]
c_{HW}	[-0.36, 0.40]	[-0.78, 0.30]	[-0.34, 0.41]	[-0.97, 0.31]	[-0.92, 0.64]	[-0.87, 0.37]