Measurement of the associated production of a Higgs boson decaying into b-quarks with a vector boson at high transverse momentum with the ATLAS detector

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ATLAS EXPERIMENT

UNIVERSITY OF OXFORD

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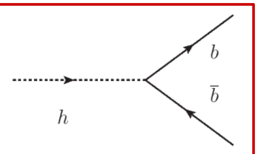
Physics motivations

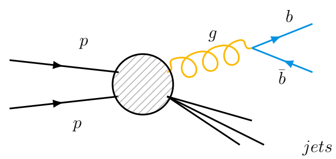
H(bb)



Largest BR in SM (~58%)

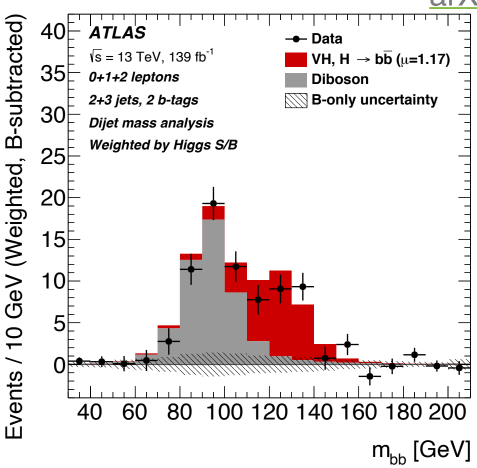
Measurement of Yukawa coupling to down-type quarks

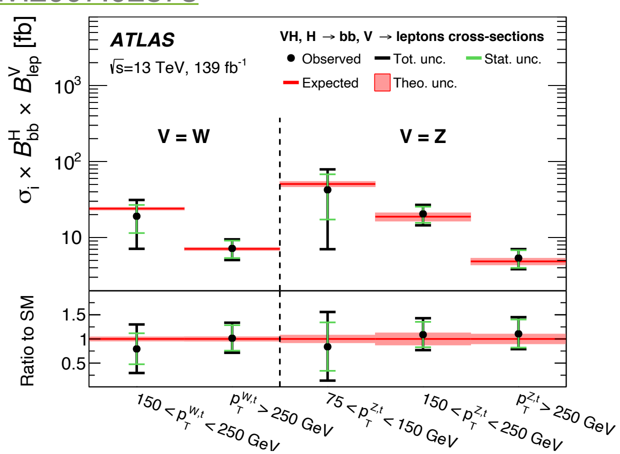
Challenge to H(bb): **large multi-jet** background

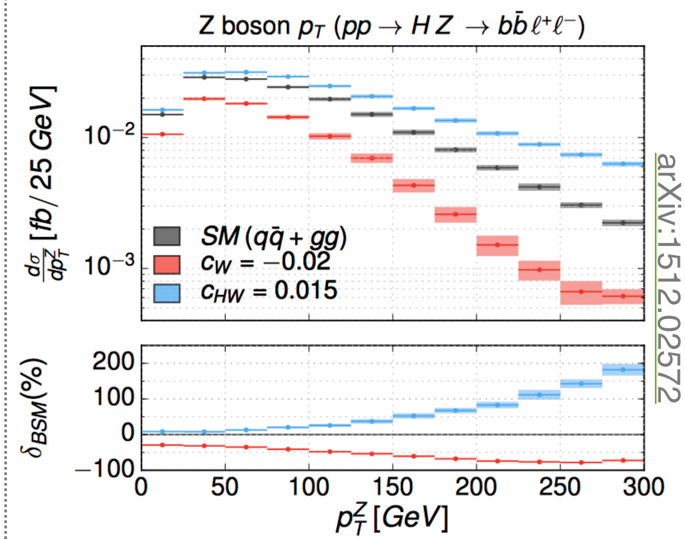


Study VH production (V=*W*,*Z*), **V→leptons**: distinctive signature, efficient trigger and large reduction of multi-jet events

arXiv:2007.02873



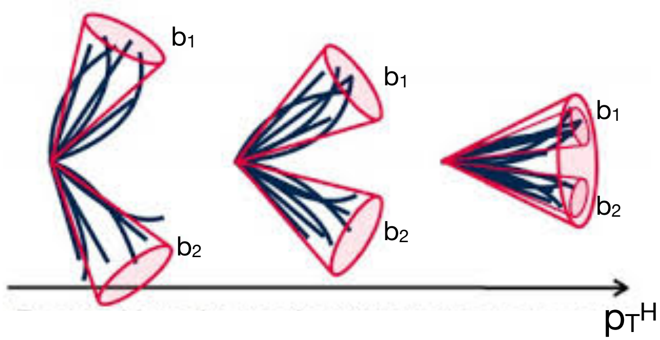




arXiv:1512.02572

- In search for new physics, BSM scenarios often predict **deviations from the SM** at **high p_T**
  - Need to have a more detailed view at this energy regime

Strategy and event selection

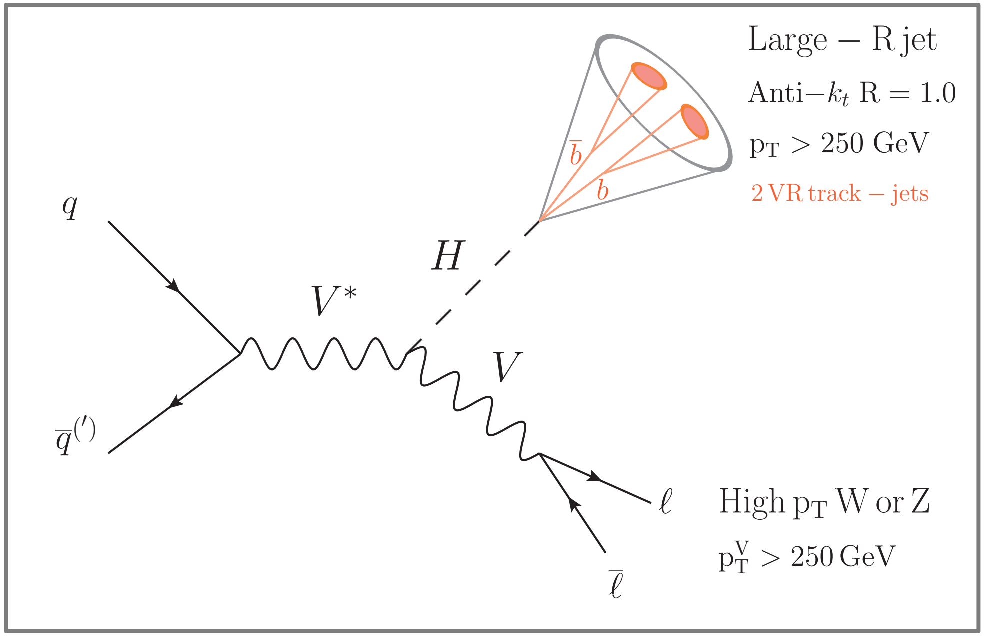


$$\Delta R(b_1, b_2) \approx \frac{2 \cdot m_H}{p_T^H}$$

$$\Delta R(b_1, b_2) \leq 1,\ p_T^H \geq 250\, GeV$$

arXiv:2008.02508

- **Higgs candidate**:
  - **Large-radius** (R) calorimeter **jet** (trimmed anti-kt R=1.0), **p_T > 250 GeV**
  - **≥ 2 variable-radius** (VR) **track jets matched** to Large-R jet
  - **Leading 2 VR track jets b-tagged** (MV2c10@70%)
- Number of charged leptons (ℓ = e,μ) in leptonic V decay determines analysis channel:
  - Z→$\nu\nu$ (0L)
  - W→$\ell\nu$ (1L)
  - Z→$\ell\ell$ (2L)

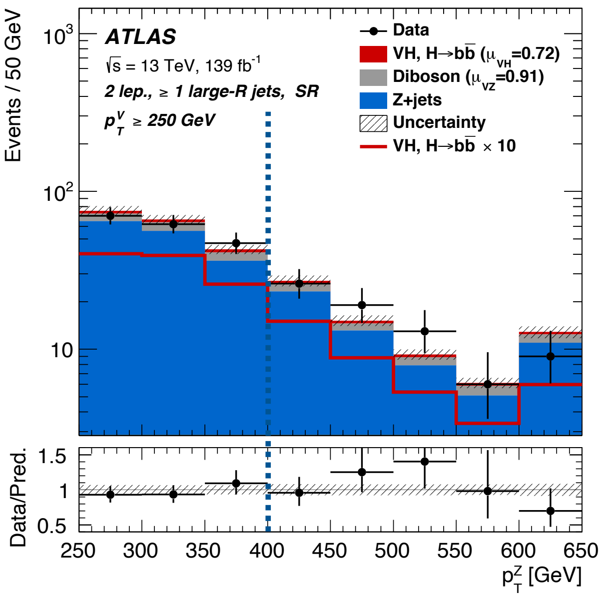


Event categorisation

arXiv:2008.02508

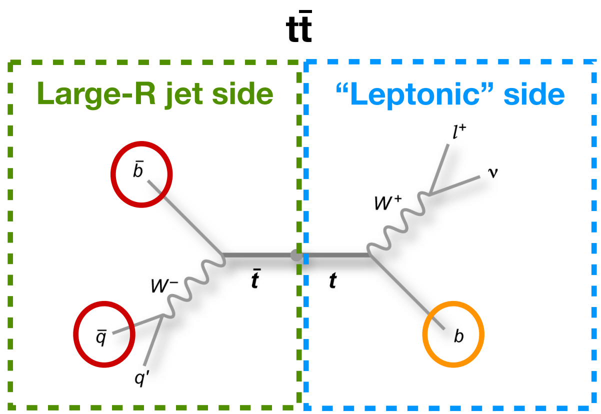
Additional categorisation for 0L and 1L

p_T^V



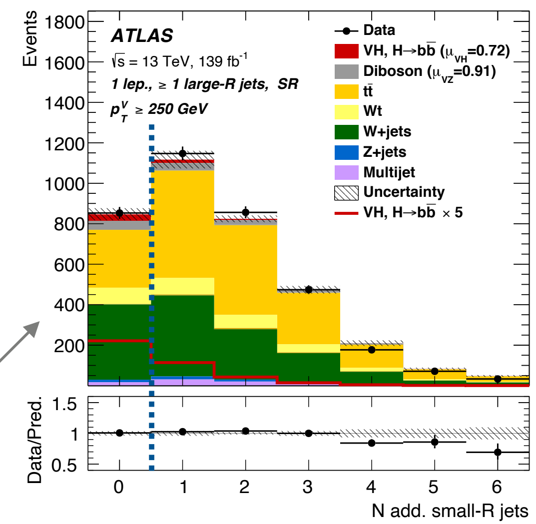
p_T^V bins: 250-400 GeV and > 400 GeV

Signal and Control Regions



- **SR** - signal-enriched region:
  - 2 **signal b-jets**: b-tagged track jets **associated to Large-R jet**
  - **0 additional b-jets**: no b-tagged track jets **not associated to Large-R jet**
- **Top CR** - top-enriched region:
  - 2 **signal b-jets**: b-tagged track jets **associated to Large-R jet**
  - **1+ additional b-jets**: 1+ b-tagged track jets **not associated to Large-R jet**

High and Low Purity Signal Regions

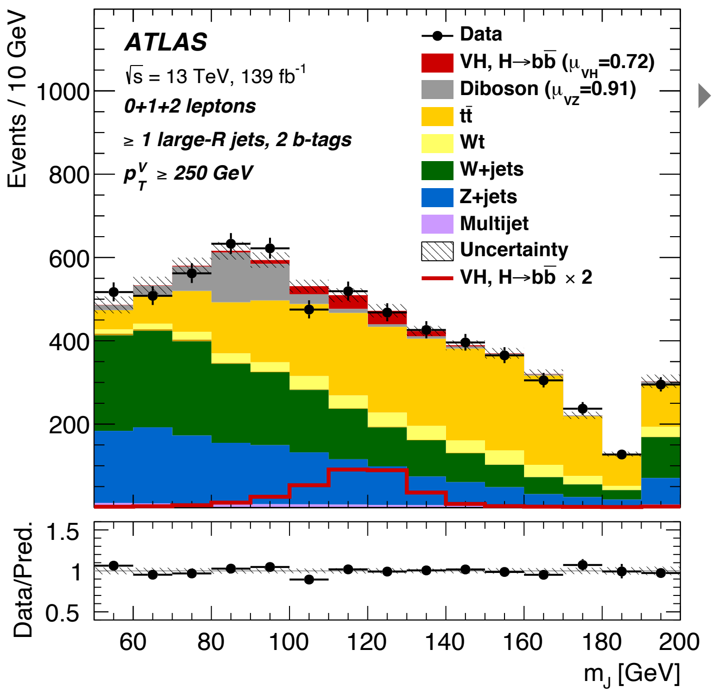


SR further divided into high (HP) and low (LP) purity categories:

- **High Purity SR**:
  - **0 additional calo-jets**: Small-R (R=0.4) calorimeter-jets not associated to Large-R jet
- **Low Purity SR**:
  - **1+ additional calo-jets**: Small-R (R=0.4) calorimeter-jets not associated to Large-R jet

arXiv:2008.02508

Background processes and fit model



- **Background modelling strategy**:
  - tt̄, W+hf, Z+hf, Diboson: dominant backgrounds, templates extracted from simulation, normalisation from data
  - Single top, V+light flavours (ll, cl)*: template and normalisation uncertainties from simulation
  - Multi-jet: suppressed with dedicated cuts, residual contribution studied in data

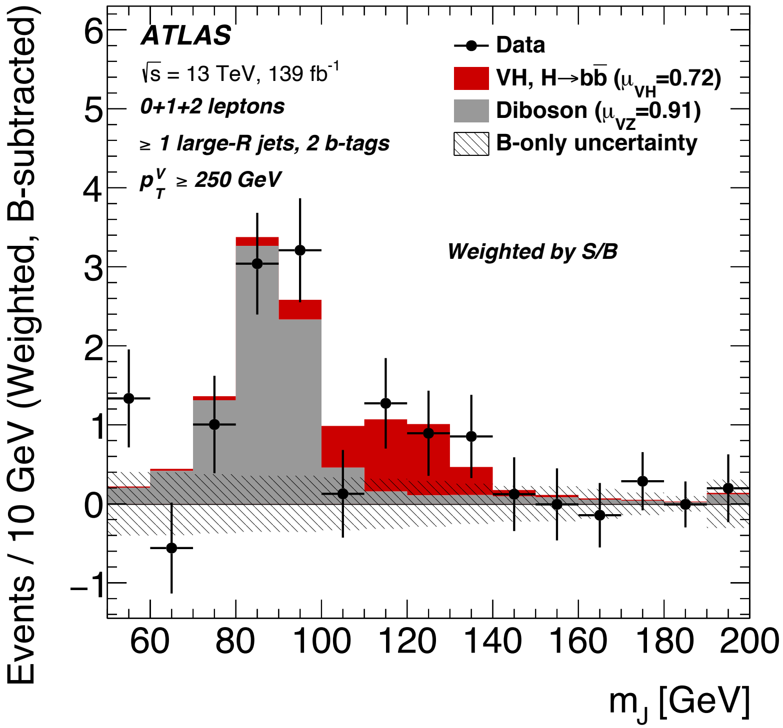
*< 5% of total V+jets

- Signal extracted using binned profile likelihood fit with Large-R jet mass (**m_J**) as discriminant
  - Fit 10 signal and 4 control regions simultaneously
- Simultaneous measurement of signal strength parameters μ_{VH} and μ_{VZ}:

$$\mu = \frac{\sigma_{meas}}{\sigma_{SM}}$$

arXiv:2008.02508

Results



Measurement	Expected sig.	Observed sig.
0L	1.86	1.43
1L	1.96	1.95
2L	1.24	-0.13
WH	1.92	2.04
ZH	1.79	0.63
combined	2.73	2.05

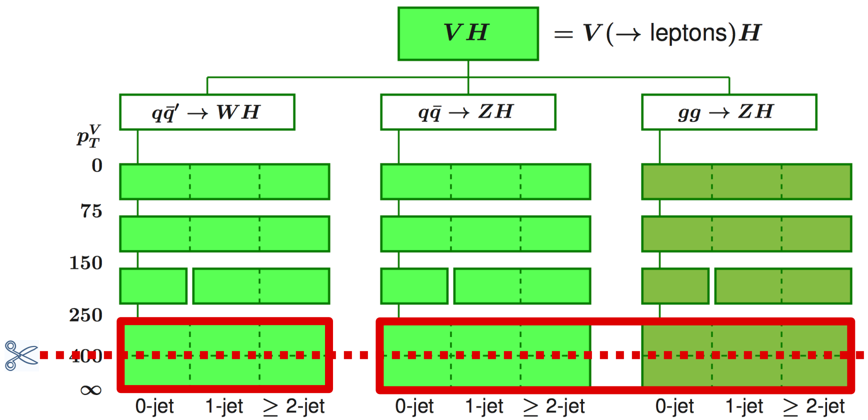
$$\mu^{bb}_{VH} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.}) \qquad \sigma^{bb}_{VH} = 2.1\,(2.7)\ obs.\,(exp.)$$

$$\mu^{bb}_{VZ} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.}) \qquad \sigma^{bb}_{VZ} = 5.4\,(5.7)\ obs.\,(exp.)$$

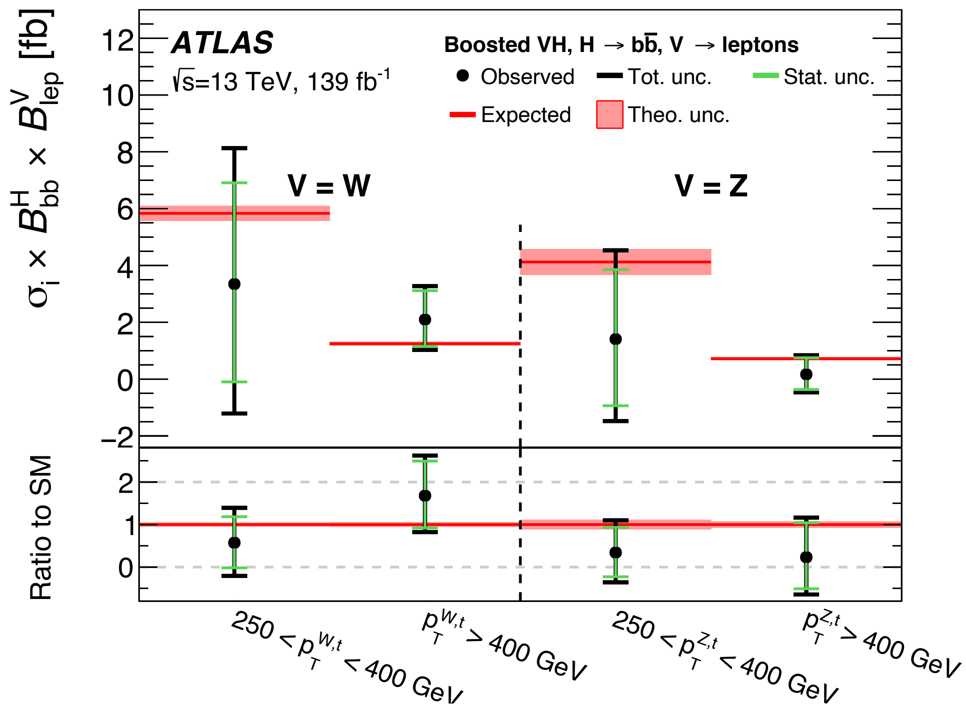
arXiv:2008.02508

Simplified Template Cross Section (STXS)

- **Differential cross section measurement** in “simplified” **fiducial regions**
- **STXS measurement** in 2 p_T^V analysis bins: [250,400[, [400,∞[



arXiv:1906.02754



Measurement	Expected sig.	Observed sig.
WH [250, 400] GeV	1.26	0.73
WH [400, ∞] GeV	1.27	2.02
ZH [250, 400] GeV	1.38	0.49
ZH [400, ∞] GeV	1.12	0.26

arXiv:2008.02508

Effective Field Theory (EFT) interpretation

- Model-independent way to test presence of BSM physics
- Parameterisation of BSM effects using effective Lagrangian operators in Warsaw basis.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Wilson coefficients

Scale of new physics (1 TeV)

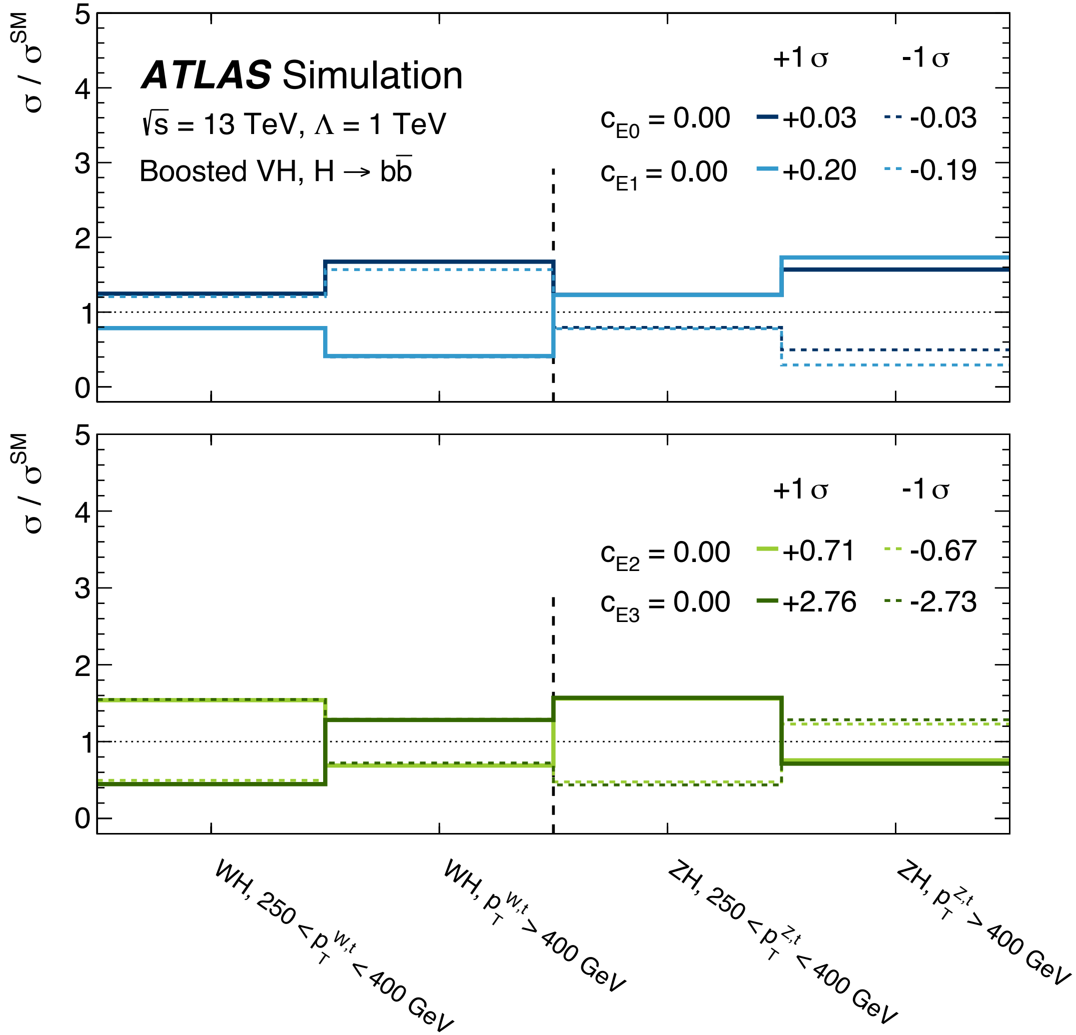
14 dimension-6 operators (Warsaw basis) describing new physics considered

- Parametrise **σ(qq→ZH), σ(qq→WH), BR(H→bb)** as linear/quadratic polynomials in $\mathbf{c_i}$
- Extract 95% CL limits for leading c_i coefficients

Coefficient	Operator
c_H	$(H^\dagger H)(H^\dagger H)$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
$\lvert c_{dH} \rvert$	$(H^\dagger H)(\bar{q}_p d_r H)$
c_{HW}	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
$c^{(1)}_{Hl}$	$H^\dagger i\overleftrightarrow{D}_\mu H(\bar{l}_p \gamma^\mu l_r)$
$c^{(3)}_{Hl}$	$H^\dagger i\overleftrightarrow{D}^I_\mu H(\bar{l}_p \tau^I \gamma^\mu l_r)$
$c^{(1)}_{He}$	$H^\dagger i\overleftrightarrow{D}_\mu H(\bar{e}_p \gamma^\mu e_r)$
$c^{(1)}_{Hq}$	$H^\dagger i\overleftrightarrow{D}_\mu H(\bar{q}_p \gamma^\mu q_r)$
$c^{(3)}_{Hq}$	$H^\dagger i\overleftrightarrow{D}^I_\mu H(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$H^\dagger i\overleftrightarrow{D}_\mu H(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$H^\dagger i\overleftrightarrow{D}_\mu H(\bar{d}_p \gamma^\mu d_r)$
$c^{(1)}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

arXiv:2008.02508

EFT results



- Effect of ±1σ variation of the **four independent deformations to the SM** the **analysis can identify**, based on the measurement of STXS bins

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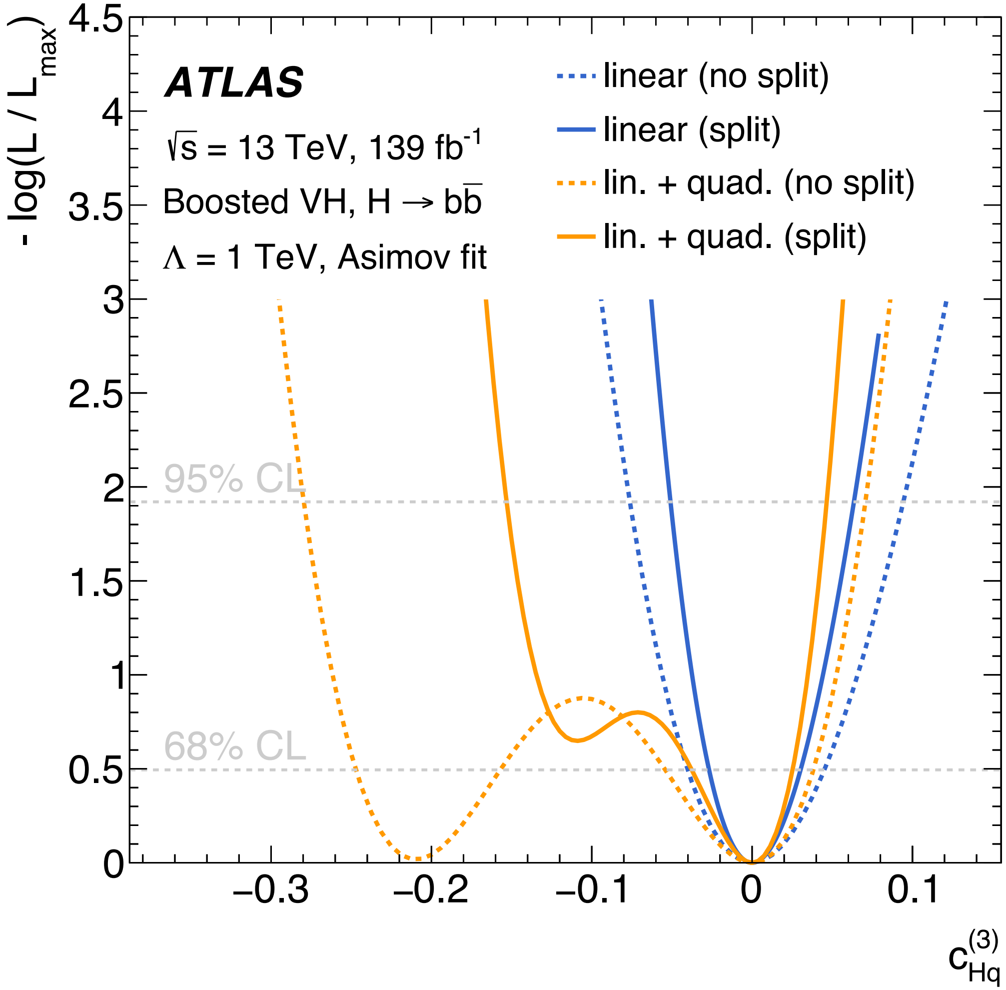
Effect of dedicated bin above 400 GeV



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Conclusions

- First VH(bb) analysis at high-p_T ($p_T^V > 250$ GeV), using boosted techniques:

$$\mu_{VH}^{bb} = 0.72^{+0.39}_{-0.36} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{syst.})$$

$$\mu_{VZ}^{bb} = 0.91^{+0.29}_{-0.23} = 0.91 \pm 0.15(\text{stat.})^{+0.25}_{-0.17}(\text{syst.})$$

- Measurement is in agreement with the SM expectations

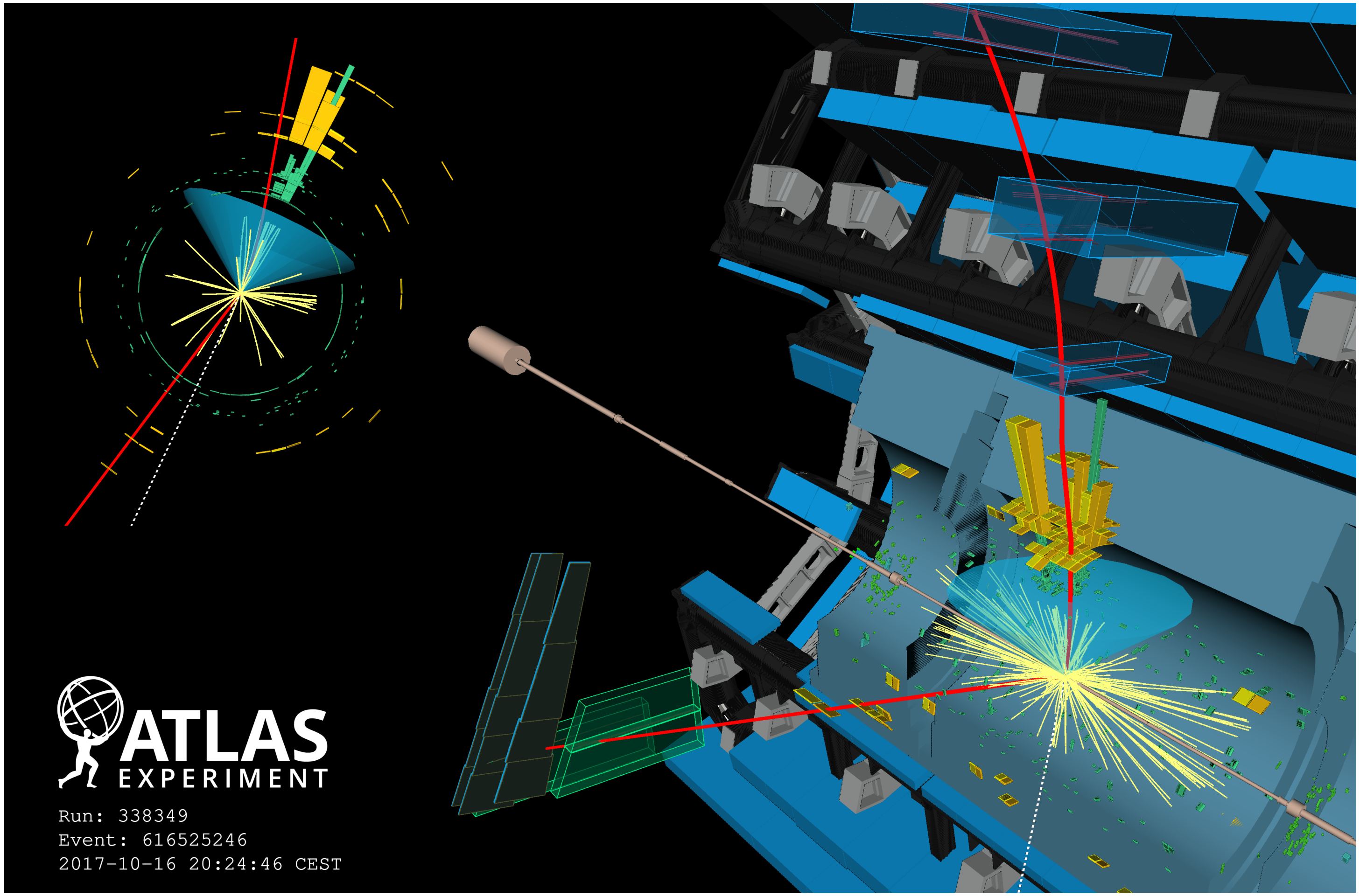
$$\sigma_{VH}^{bb} = 2.1\,(2.7)\ obs.\,(exp.)$$

$$\sigma_{VZ}^{bb} = 5.4\,(5.7)\ obs.\,(exp.)$$

- First STXS measurement of p_T(V,truth) > 400 GeV, well in agreement with SM prediction

- Provided EFT interpretation of the results

Thank you!



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CERN Physics briefing: link

Backup

Event selection details

Selection	0 lepton channel	1 lepton channel		2 leptons channel	
		e sub-channel	μ sub-channel	e sub-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	$p_{\mathrm{T}} > 25$ GeV	2 *baseline* leptons among which ≥ 1 *signal* lepton, $p_{\mathrm{T}} > 27$ GeV both leptons of the same flavour -	opposite sign muons
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 250 GeV	> 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, $\lvert\eta\rvert < 2.5$, matched to the leading large-R jet				
b-jets	leading two track-jets matched to the leading large-R must be b-tagged (MV2c10, 70%)				
m_{J}	> 50 GeV				
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R \text{ jets})]$	$> 30^{\circ}$	-			
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, H_{\mathrm{cand}})$	$> 120^{\circ}$	-			
$\Delta\phi\ (\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,\ trk}}^{\mathrm{miss}})$	$< 90^{\circ}$	-			
$\Delta y(V, H_{\mathrm{cand}})$	-	$\lvert\Delta y(V, H_{\mathrm{cand}})\rvert < 1.4$			
$m_{\ell\ell}$	-			66 GeV $< m_{\ell\ell} <$ 116 GeV	
Lepton p_{T} imbalance	-			$(p_{\mathrm{T}}^{\ell_1} - p_{\mathrm{T}}^{\ell_2})/p_{\mathrm{T}}^{Z} < 0.8$	

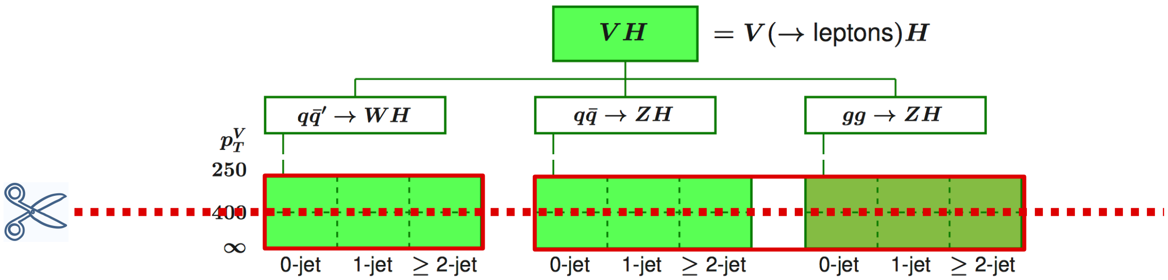
Event categorisation details

Channel	Categories					
	$250 < p_T^V < 400$ GeV			$p_T^V \geq 400$ GeV		
	0 add. b-track-jets		≥ 1 add. b-track-jets	0 add. b-track-jets		≥ 1 add. b-track-jets
	0 add. small-R jets	≥ 1 add. small-R jets		0 add. small-R jets	≥ 1 add. small-R jets	
0-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
1-lepton	HP SR	LP SR	CR	HP SR	LP SR	CR
2-lepton	SR			SR		

arXiv:2008.02508

Fit main features

- **Normalisation** of three **dominant bkgs** are **floated**:
  - ttbar → from CR
  - V+hf: W+hf, Z+hf → from sidebands in the SRs.
- **Systematics**:
  - **Full** set of **detector systematics:**
    - **Large-R jets** (pT, mass)x(scale, resolution)
    - small-R jets, MET, leptons, b-tagging, pile-up, luminosity
  - **Full set of modelling uncertainties**
  - **MC stat.** unc.: includes VZ but excludes VH (1 NP per bin)
- 2 p_T^V analysis bins (for STXS): [250,400], [400,∞]

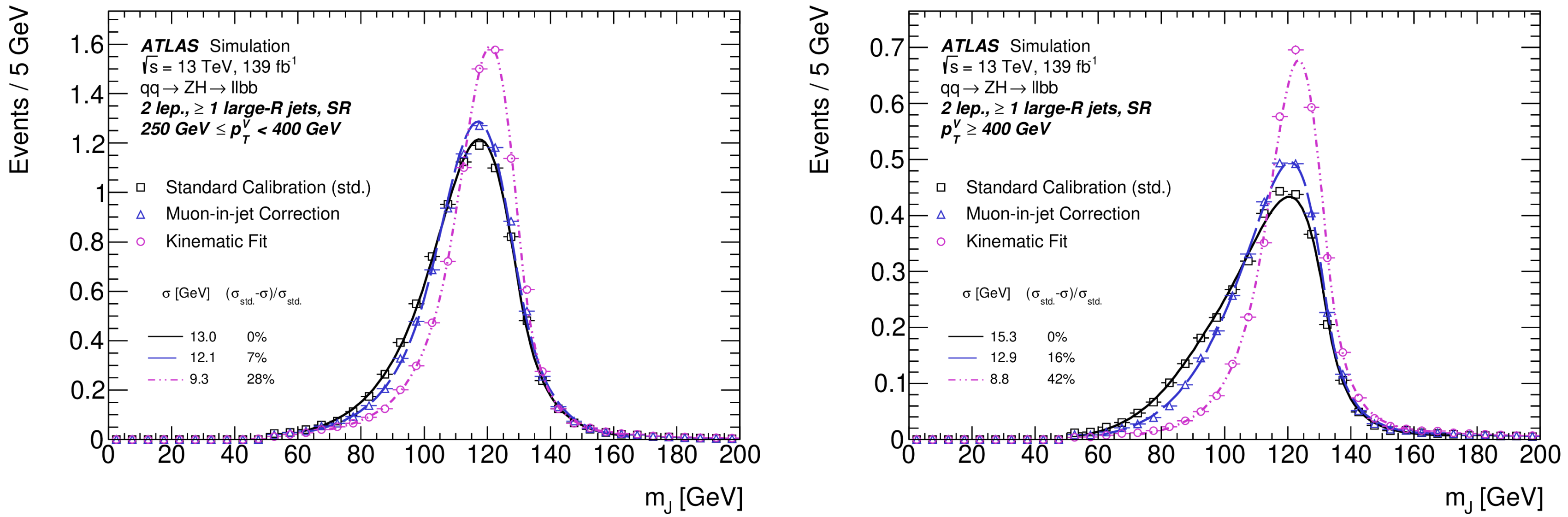


Breakdown of the uncertainties

Source of uncertainty		Avg. impact
Total		0.372
Statistical		0.283
Systematic		0.240
Experimental uncertainties		
Small-R jets		0.038
Large-R jets		0.133
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.007
Leptons		0.010
b-tagging	b-jets	0.016
	c-jets	0.011
	light-flavour jets	0.008
	extrapolation	0.004
Pile-up		0.001
Luminosity		0.013
Theoretical and modelling uncertainties		
Signal		0.038
Backgrounds		0.100
$\hookrightarrow$ Z + jets		0.048
$\hookrightarrow$ W + jets		0.058
$\hookrightarrow$ $t\bar{t}$		0.035
$\hookrightarrow$ Single top quark		0.027
$\hookrightarrow$ Diboson		0.032
$\hookrightarrow$ Multijet		0.009
MC statistical		0.092

- Analysis statistically limited.
- Systematic uncertainties is of same order as the statistical one. Most relevant sources:
  - **Large-R jets (JMR, then JMS)**
  - **Modelling uncertainties**
  - MC stat.

Large-R jet mass



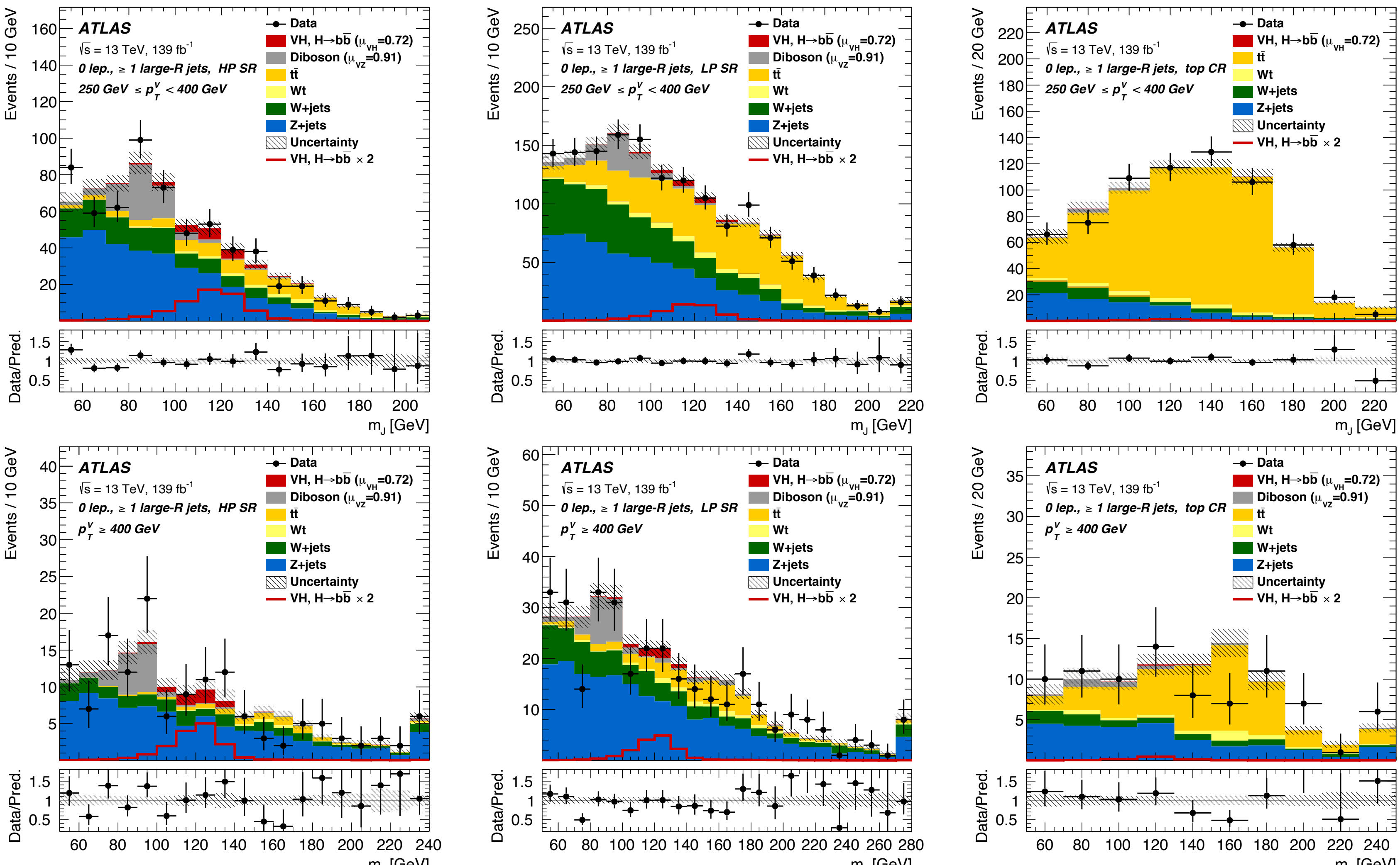
- Final discriminant: Large-R jet mass (**m_J**). Improve mass resolution on top of calorimeter-based performance using:
  - Combined mass
  - Muon-in-jet-correction
  - Kinematic fit (2L)

Postfit plots: 0L

HP SR | LP SR | CR

250 GeV < p_T^V < 400 GeV

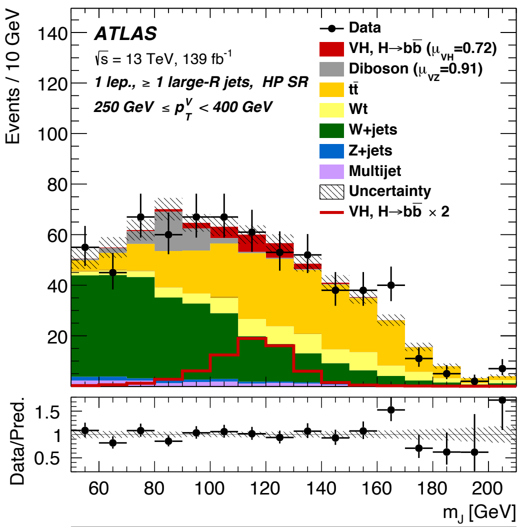
p_T^V > 400 GeV

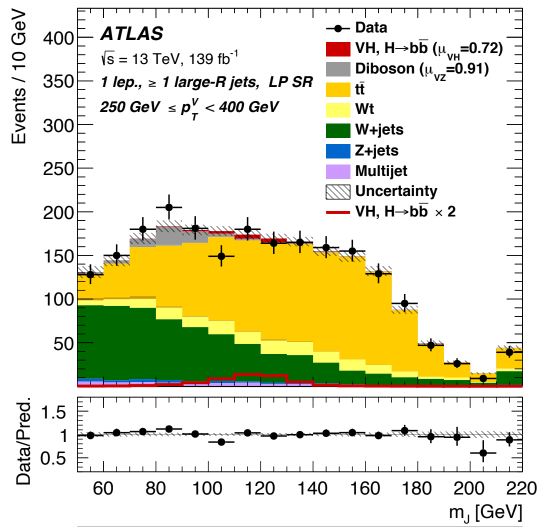


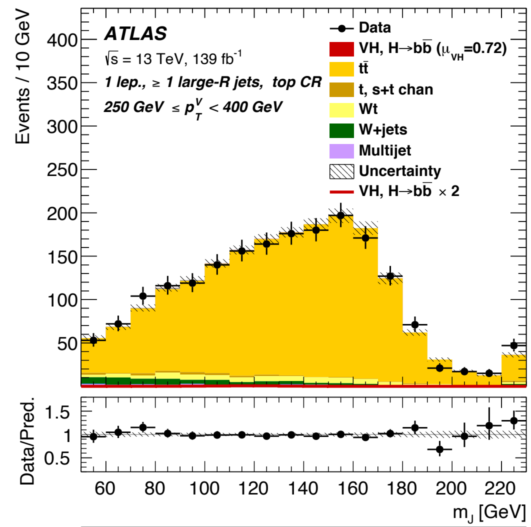
Postfit plots: 1L

HP SR | LP SR | CR

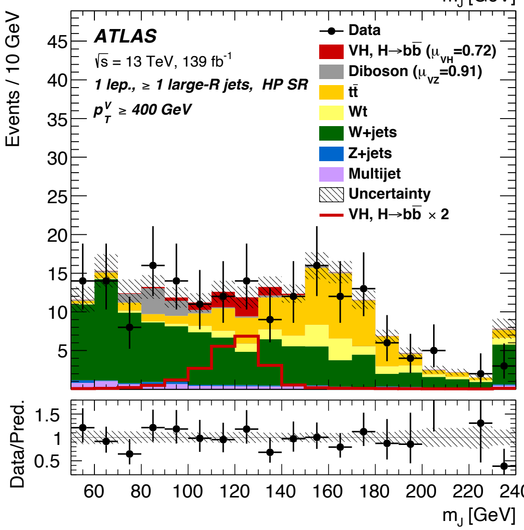
$250\ \text{GeV} < p_T^V < 400\ \text{GeV}$

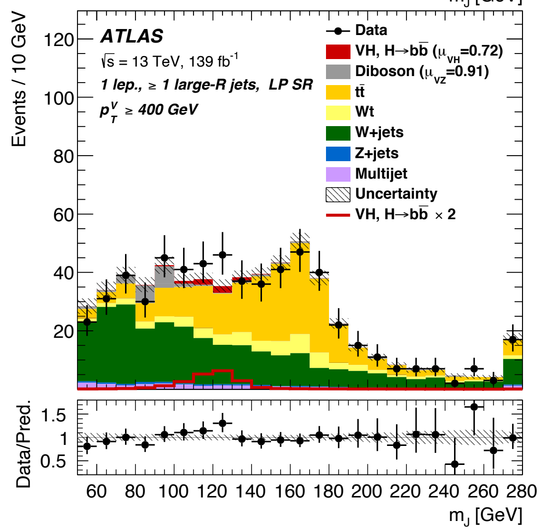


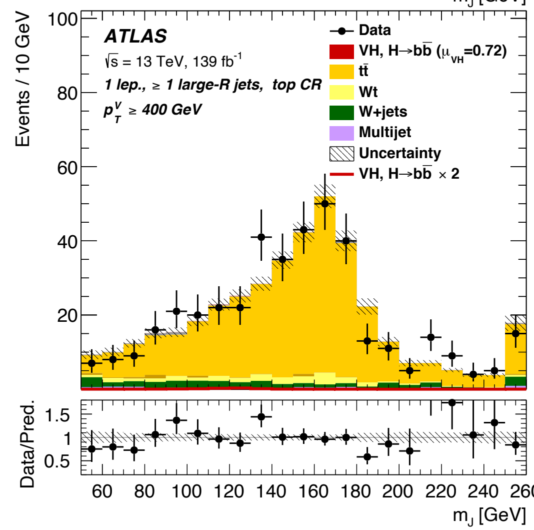




$p_T^V > 400\ \text{GeV}$

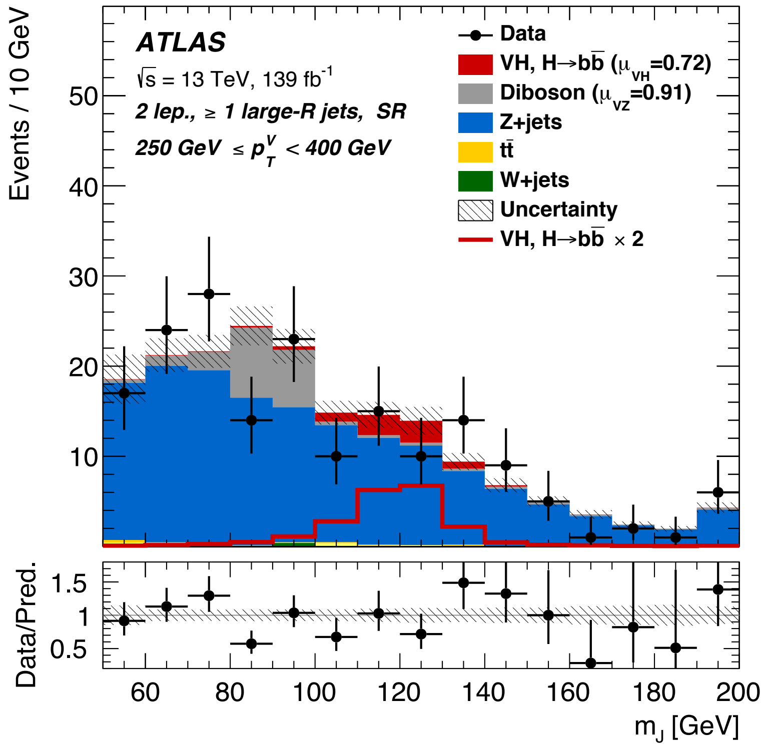


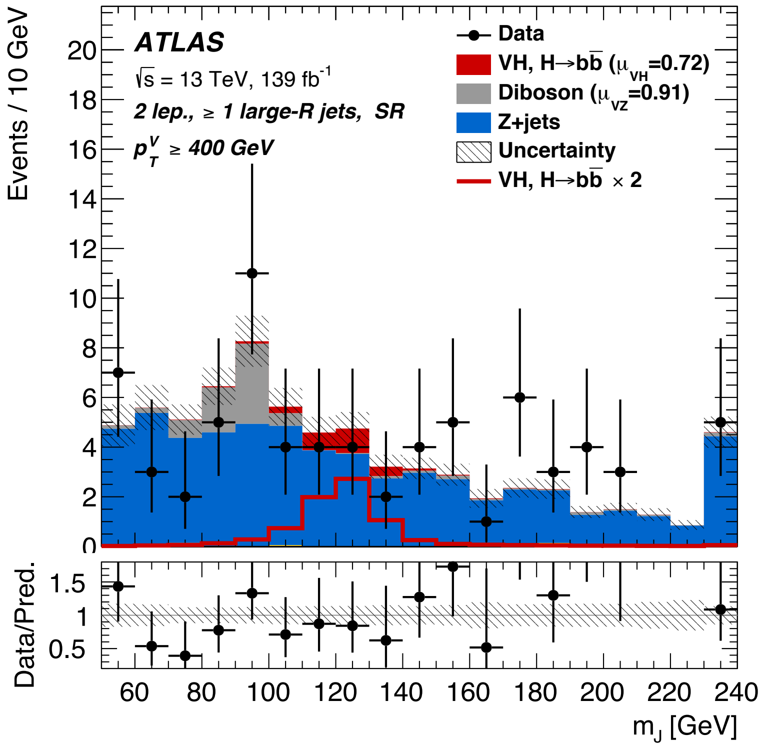




Postfit plots: 2L

SR





250 GeV < p_T^V < 400 GeV

p_T^V > 400 GeV

Postfit event yields: 0L

Processes	250 GeV $< p_{\mathrm{T}}^{V} \leq$ 400 GeV			$p_{\mathrm{T}}^{V} >$ 400 GeV		
	HP SR	LP SR	CR	HP SR	LP SR	CR
$W + t$	14.7±5.4	46±19	17.2±8.1	2.0±1.0	8.93±6.3	3.76±2.5
other $t + X$	0.79±0.03	3.18±0.66	4.5±1.3	-	0.66±0.03	0.1091±0.0041
$t\bar{t}$	75±14	423±36	539±31	7.5±1.8	38.21±6.8	44.07±7.43
VZ	77±17	88±19	6.2±1.6	17.3±4.1	28.77±6.6	2.79±0.72
WW	-	2.15±0.05	0.24±0.01	0.33±0.02	1.80±0.06	-
W+HF	101±20	331±60	30±22	20.2±6.2	59.8±18	6.6±5.1
$W + cl$	5.1±2.3	8.4±3.2	0.46±0.01	0.99±0.69	2.8±1.1	0.19±0.07
$W + l$	5.6±3.9	4.6±2.5	0.160±0.003	1.4±2.0	2.7±1.7	0.57±0.36
Z+HF	319±35	549±62	77±21	87±11	185±21	25.8±7.4
$Z + cl$	4.0±1.6	6.7±2.7	0.83±0.02	-	6.4±2.7	0.93±0.41
$Z + l$	1.34±0.67	3.6±2.1	0.42±0.01	1.05±0.63	3.7±2.5	0.29±0.16
Signal	22±11	19.0±9.8	1.05±0.54	5.7±2.9	5.9±3.0	0.33±0.17
Background	603±25	1466±36	676±25	137.6±8.5	339±15	85.1±7.3
data	623	1493	683	146	330	85

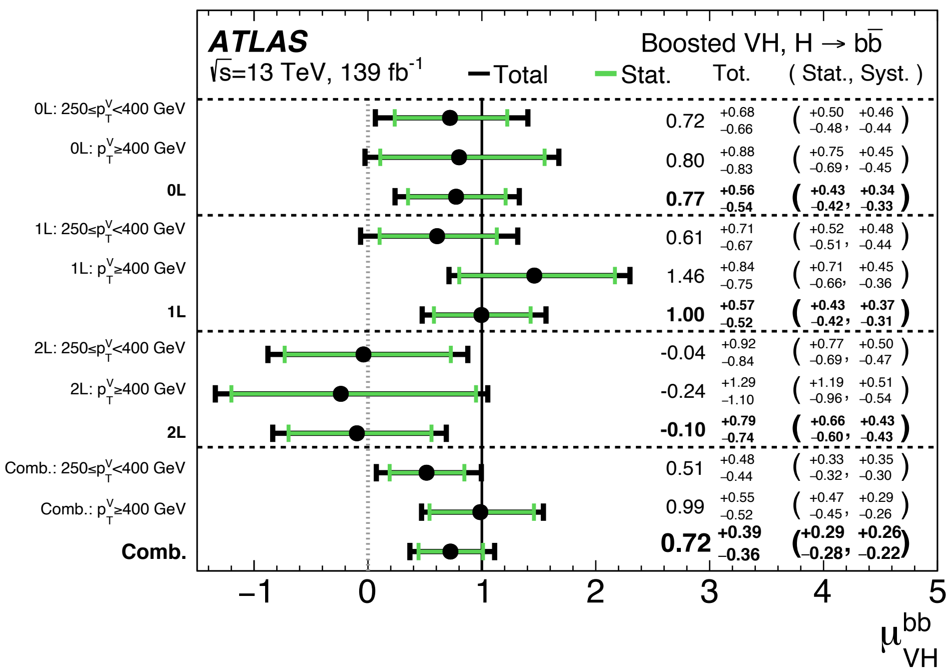
Postfit event yields: 1L

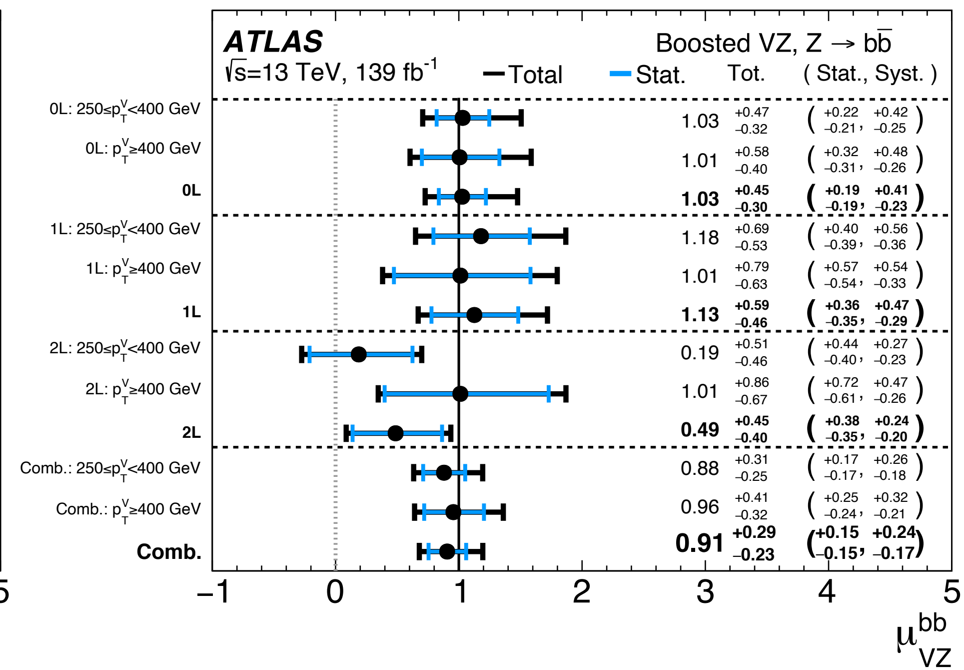
Processes	$250\text{ GeV} < p_{\mathrm{T}}^{V} \leq 400\text{ GeV}$			$p_{\mathrm{T}}^{V} > 400\text{ GeV}$		
	HP SR	LP SR	CR	HP SR	LP SR	CR
$W+t$	64±21	160±75	73±30	16.4±7.3	53±42	21±15
other $t+X$	1.92±0.48	16.3±0.3	21.9±6.2	0.13±0.01	1.70±0.06	4.0±1.4
$t\bar{t}$	235±30	1190±76	1758±58	50.9±7.3	227±24	341±25
VZ	35.9±8.9	56±14	5.0±1.4	8.63±2.3	20.0±5.3	2.61±0.84
WW	-	6.8±1.6	0.27±0.01	0.15±0.02	4.68±1.32	0.93±0.03
W+HF	265±28	617±64	60±22	91±12	239±30	26.6±9.8
$W+cl$	7.33±2.9	13.8±5.7	2.10±0.04	6.2±2.5	10.2±4.1	0.63±0.02
$W+l$	3.0±1.5	5.7±3.4	0.65±0.01	2.2±1.4	7.7±5.0	0.31±0.01
Z+HF	10.2±1.2	24.6±2.5	3.45±0.41	2.12±0.30	6.56±0.79	0.98±0.12
$Z+cl$	-	0.75±0.02	-	-	0.33±0.01	-
$Z+l$	-	0.49±0.01	-	0.30±0.19	0.23±0.01	-
MultiJet	17.0±8.9	44±23	22±11	7.8±4.5	22±13	7.9±4.0
Signal	24±12	18.0±9.3	0.86±0.45	7.8±4.0	7.5±3.9	0.39±0.20
Background	640±26	2136±44	1947±43	186±11	592±21	406±18
data	668	2161	1946	185	597	410

Postfit event yields: 2L

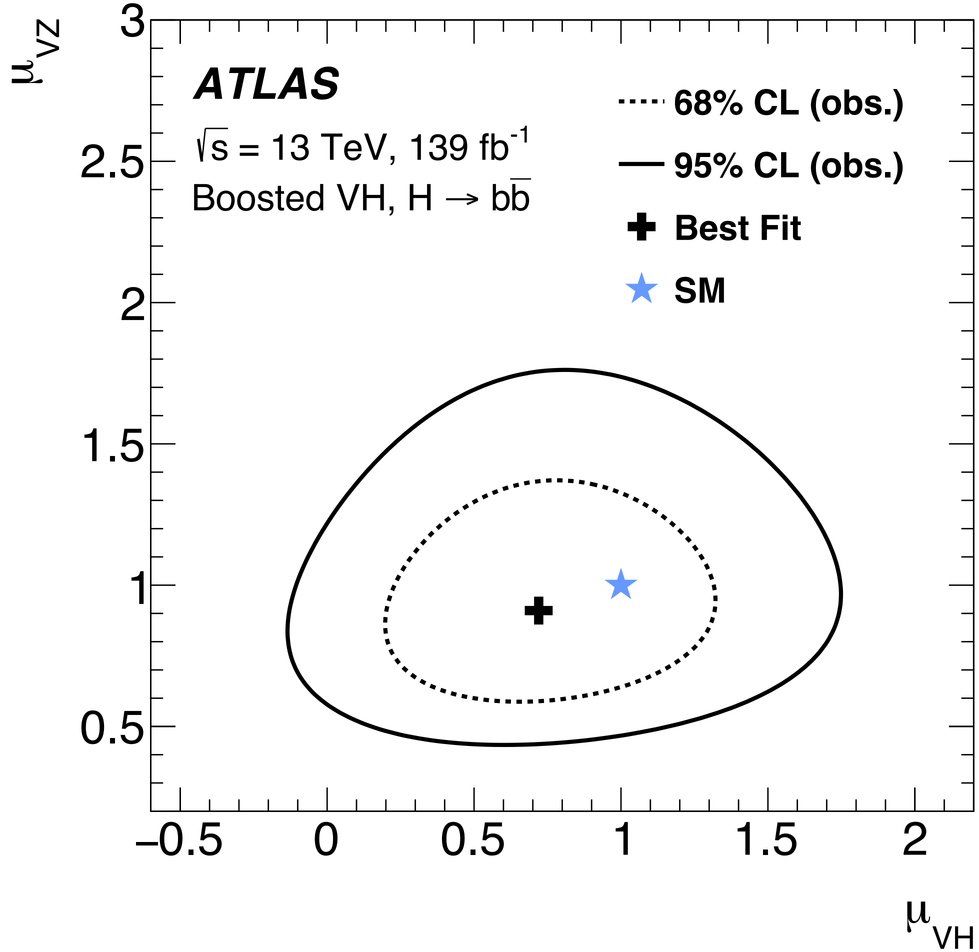
Processes	$250\ \text{GeV} < p_{\text{T}}^{V} \leq 400\ \text{GeV}$ SR	$p_{\text{T}}^{V} > 400\ \text{GeV}$ SR
$W+t$	1.28±0.39	-
$t\bar{t}$	1.64±0.35	0.45±0.10
VZ	19.9±4.9	7.5±2.1
W+HF	0.41±0.07	0.07±0.01
Z+HF	151±13	57.2±5.8
$Z+cl$	2.20±0.91	1.80±0.76
$Z+l$	0.94±0.67	1.01±0.67
Signal	7.6±3.9	2.8±1.4
Background	177±12	68.0±5.6
data	179	73

Multi POI fits: μ_{VH} and μ_{VZ}



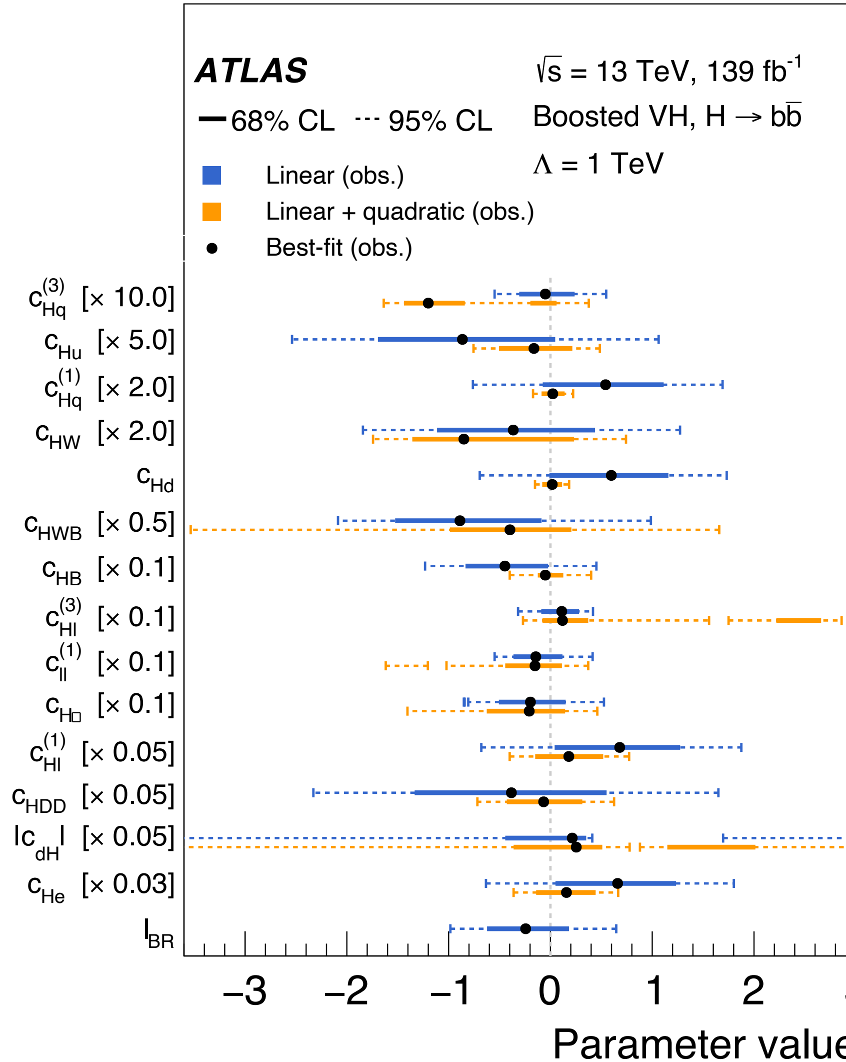


Measured CL μ_{VH} and μ_{VZ}



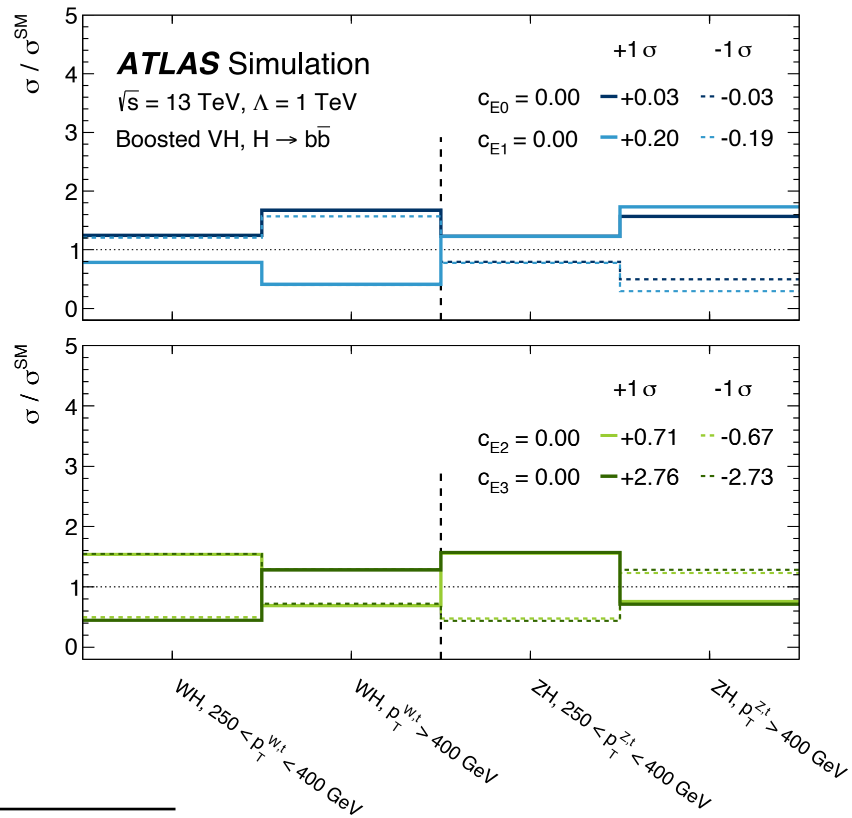
EFT interpretation results

Coefficient	Operator
c_H	$(H^\dagger H)(H^\dagger H)$
c_{HDD}	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
$\lvert c_{dH} \rvert$	$(H^\dagger H)(\bar{q}_p d_r H)$
c_{HW}	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
c_{HB}	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$
$c^{(1)}_{Hl}$	$H^\dagger i \overleftrightarrow{D}_\mu H (\bar{l}_p \gamma^\mu l_r)$
$c^{(3)}_{Hl}$	$H^\dagger i \overleftrightarrow{D}^I_\mu H (\bar{l}_p \tau^I \gamma^\mu l_r)$
$c^{(1)}_{He}$	$H^\dagger i \overleftrightarrow{D}_\mu H (\bar{e}_p \gamma^\mu e_r)$
$c^{(1)}_{Hq}$	$H^\dagger i \overleftrightarrow{D}_\mu H (\bar{q}_p \gamma^\mu q_r)$
$c^{(3)}_{Hq}$	$H^\dagger i \overleftrightarrow{D}^I_\mu H (\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$H^\dagger i \overleftrightarrow{D}_\mu H (\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$H^\dagger i \overleftrightarrow{D}_\mu H (\bar{d}_p \gamma^\mu d_r)$
$c^{(1)}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$



arXiv:2008.02508

EFT results



Coefficient	Expected	Observed
c_{EA}	$0.000^{+0.030}_{-0.027}$	$-0.010^{+0.027}_{-0.025}$
c_{EB}	$0.00^{+0.20}_{-0.19}$	$-0.21^{+0.19}_{-0.20}$
c_{EC}	$0.00^{+0.71}_{-0.67}$	$-0.62^{+0.70}_{-0.66}$
c_{ED}	$0.0^{+2.8}_{-2.7}$	$0.4^{+2.8}_{-2.7}$

Coefficient	Eigenvalue	Eigenvector combination
c_{EA}	1500.0	$0.99 \cdot c_{Hq}^{(3)} + 0.11 \cdot c_{Hu}$
c_{EB}	26.9	$0.82 \cdot c_{Hu} - 0.49 \cdot c_{Hq}^{(1)} - 0.24 \cdot c_{Hd} - 0.13 \cdot c_{Hq}^{(3)}$
c_{EC}	2.2	$0.67 \cdot \mathcal{I}_{BR} + 0.66 \cdot c_{HW} + 0.18 \cdot c_{Hq}^{(1)} - 0.16 \cdot c_{Hl}^{(3)} + 0.14 \cdot c_{HWB} + 0.12 \cdot c_{ll}^{(1)}$
c_{ED}	0.1	$0.70 \cdot c_{Hq}^{(1)} + 0.52 \cdot c_{HWB} + 0.27 \cdot c_{Hu} - 0.27 \cdot c_{HW} - 0.24 \cdot c_{Hd} + 0.13 \cdot c_{HB}$