ATLAS EXPERIMENT

$VH(H \rightarrow bb)$ Measurements and EFT Interpretation in ATLAS

Cecilia Tosciri

University of Oxford

UNIVERSITY OF OXFORD

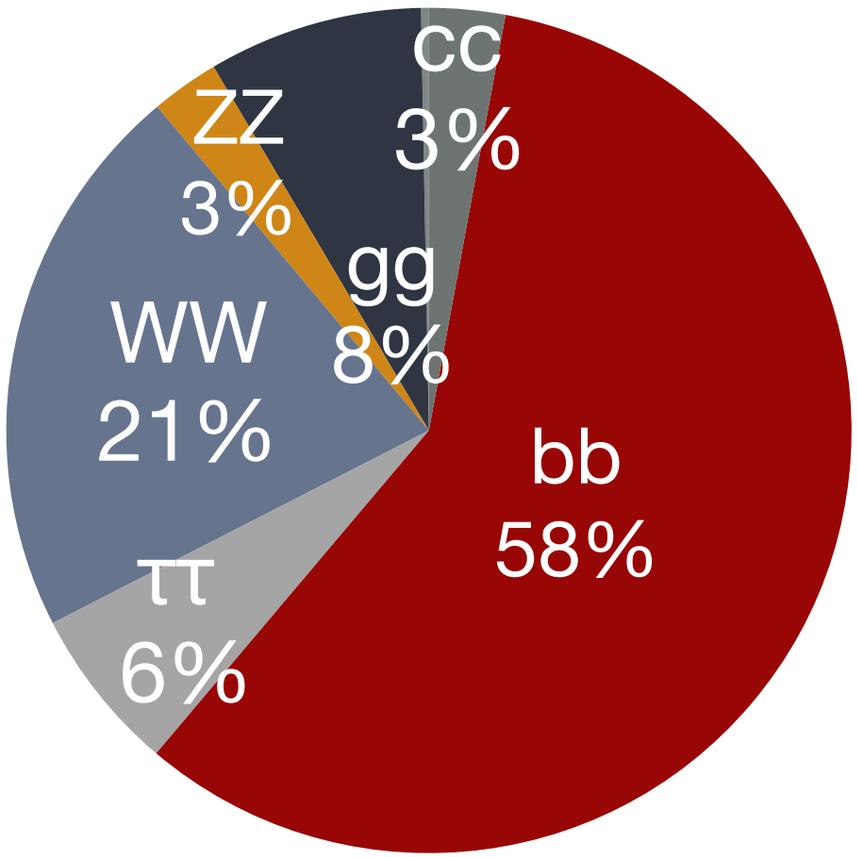
Higgs Hunting, Paris 29th February 2019

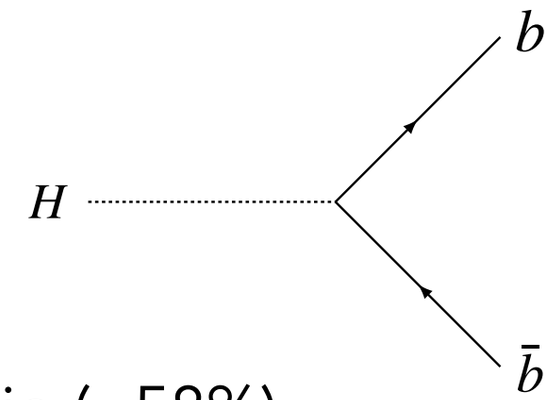
Outline

Observation during Run 2 of *VH* production and *bb* decays with full 2015-2017 data (79.8 fb^{-1}) Phys. Lett. B 786 (2018) 59

Measurement of $VH(H \rightarrow bb)$ production as a function of the vector-boson transverse momentum JHEP05(2019)141 including Effective Field Theory (EFT) interpretation

$VH(H \to bb)$



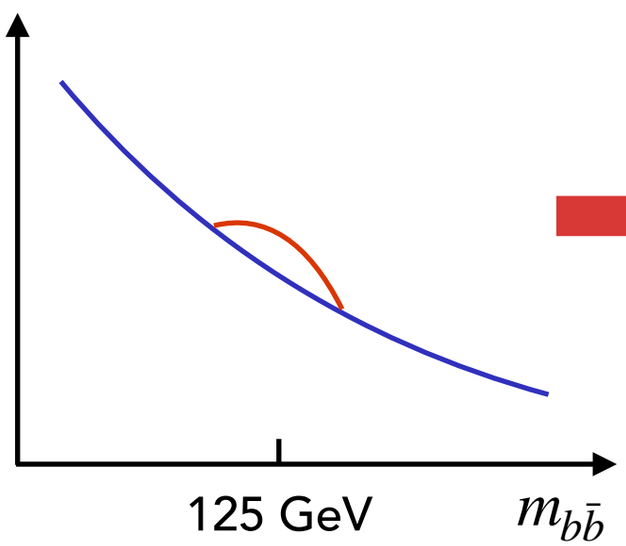


$H \to bb$

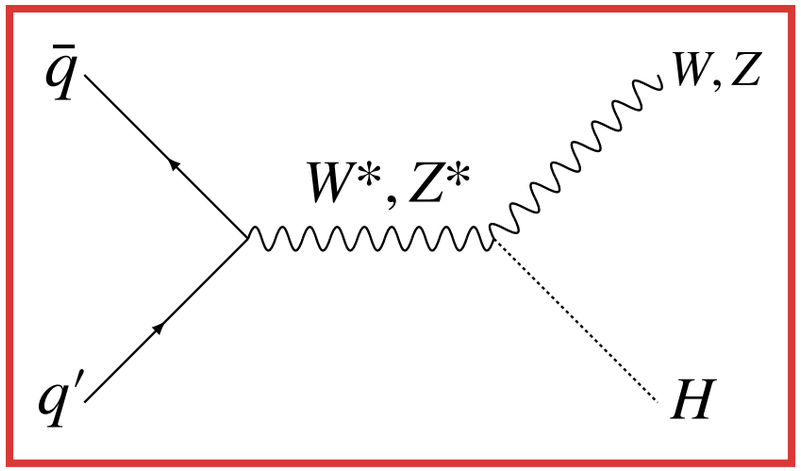
- Largest branching ratio (~58%)
- First direct measurement of Yukawa coupling with down-type quarks
- Can provide constraints on BSM physics

Limitation

Very large multi-*b*-jets production cross section at the LHC



VH, 3% of total *H* production

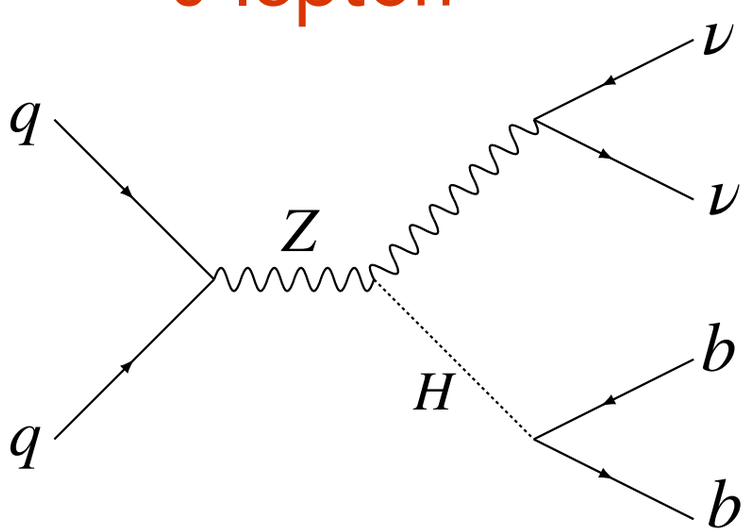


- Most sensitive channel
- Reduced background

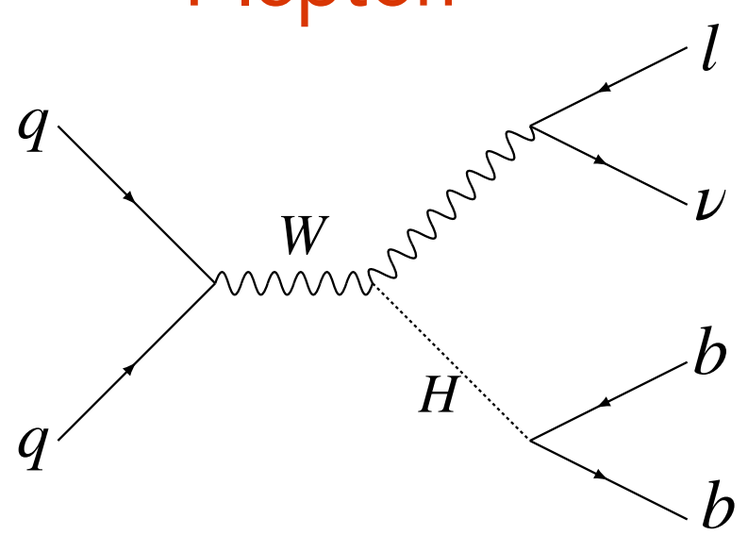
Event Selection for $VH(H \rightarrow bb)$

- Leptonic decays of Z/W: efficient triggering and bkg rejection
- 3 channels according to the number of **leptons (0, 1, 2)**
- Exactly **2 *b*-tagged jets** with 0 or 1(+) additional jets
- Define categories based on number of leptons, jets and p_T^V (transverse momentum of the vector boson V)

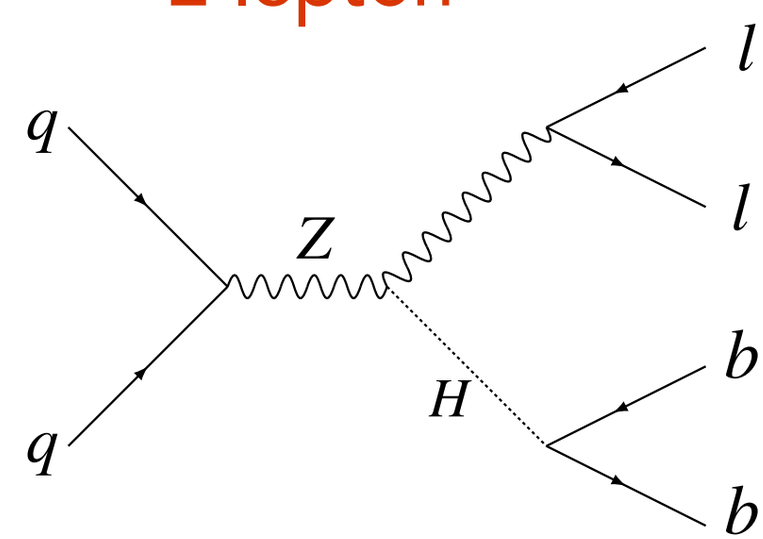
0-lepton



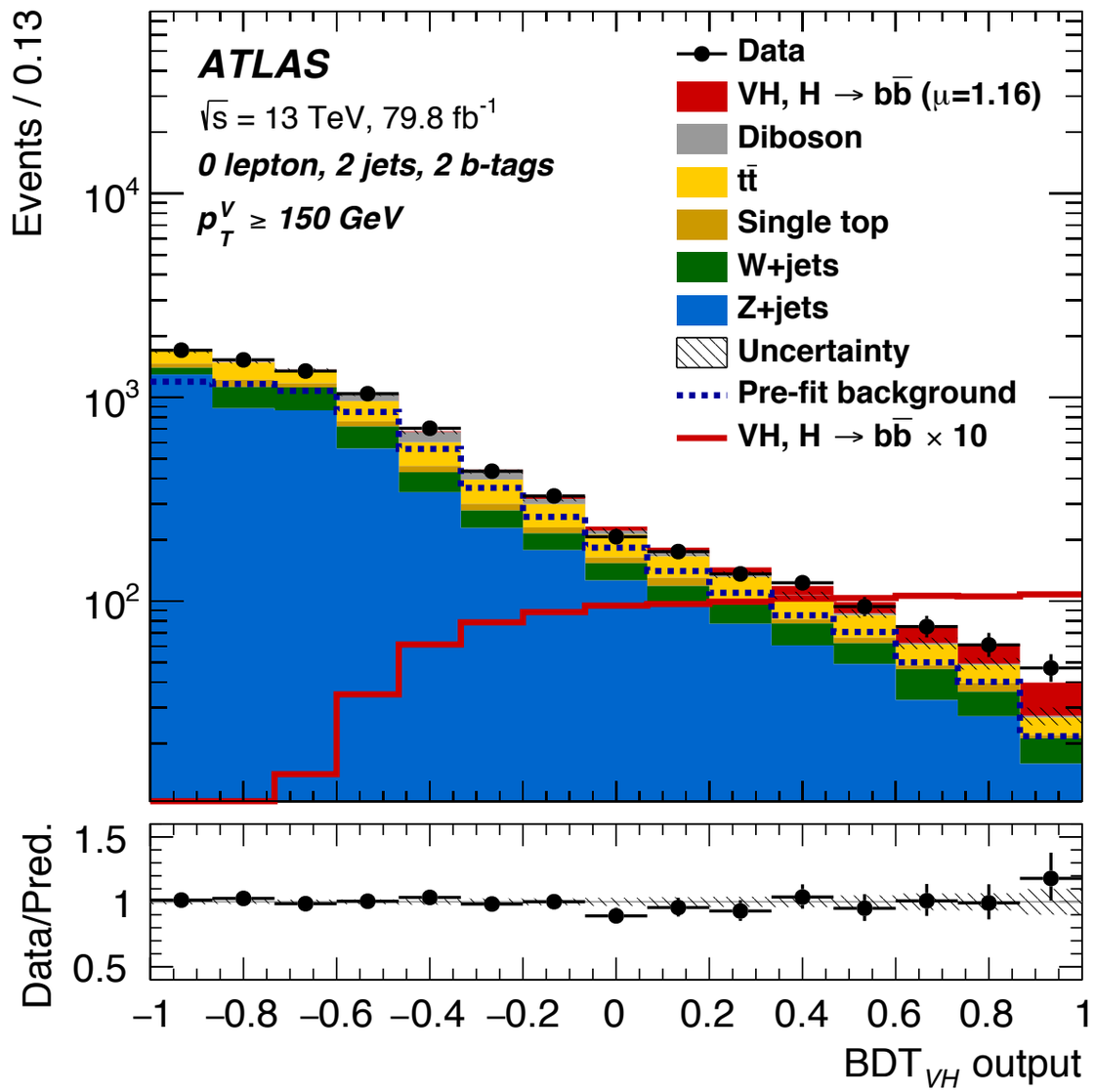
1-lepton



2-lepton



Multivariate Analysis (MVA)

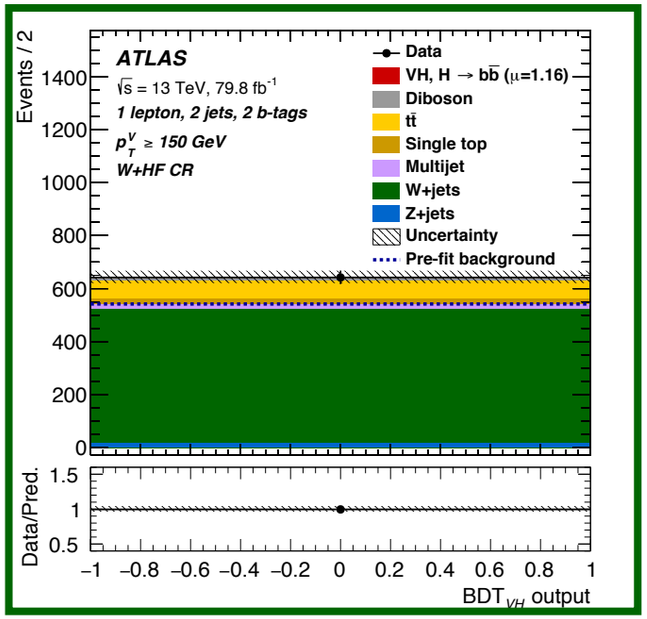


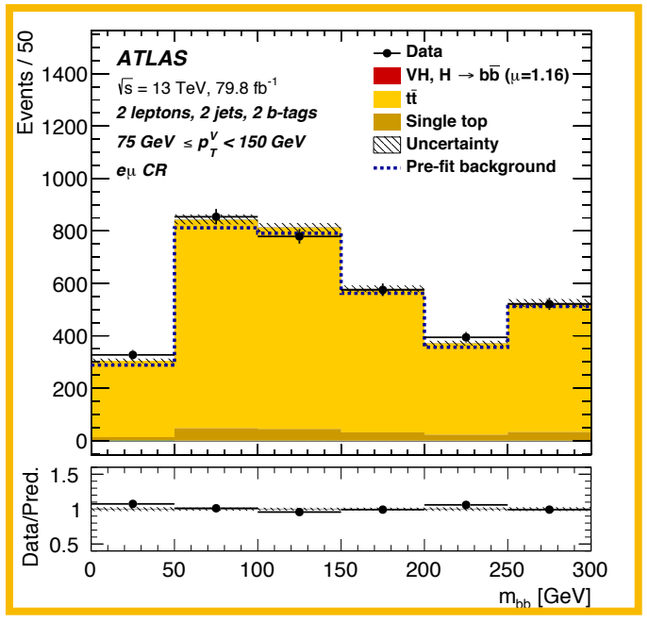
- Discrimination between signal and background increased by a **MVA**
- **Boosted Decision Tree** (BDT) trained separately for each category
- Observables combined into the BDT: m_{bb}, ΔR_{bb}, p_T^V most important

Statistical Analysis

Binned maximum likelihood fit to BDT discriminants simultaneously in all categories to extract signal strength μ and normalisation of main backgrounds

- **8 Signal Regions** (SRs)
- Constrain shape + normalisation of bkgs from data using **Control Regions** (CRs)
- **2 W+HF** (heavy flavour) CRs in 1-lepton
- **4 top eμ** CRs in 2-lepton
- Main bkg normalisations unconstrained
- Dependence on syst. uncertainties described by nuisance parameters

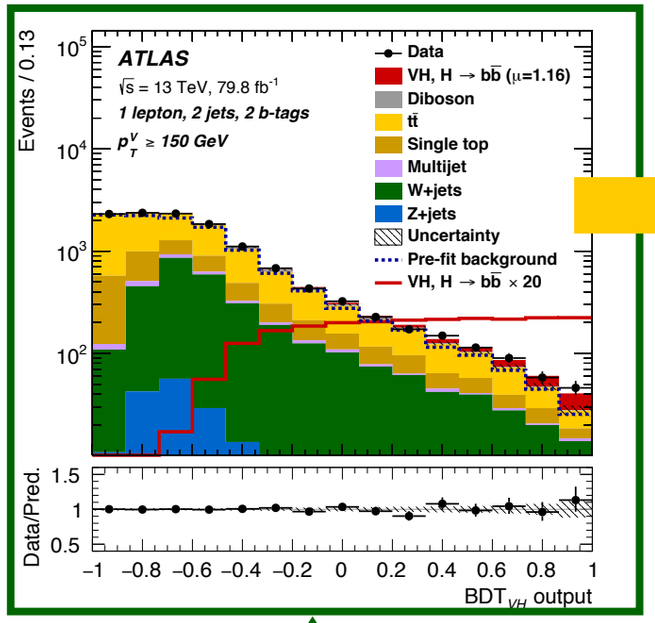




Statistical Analysis

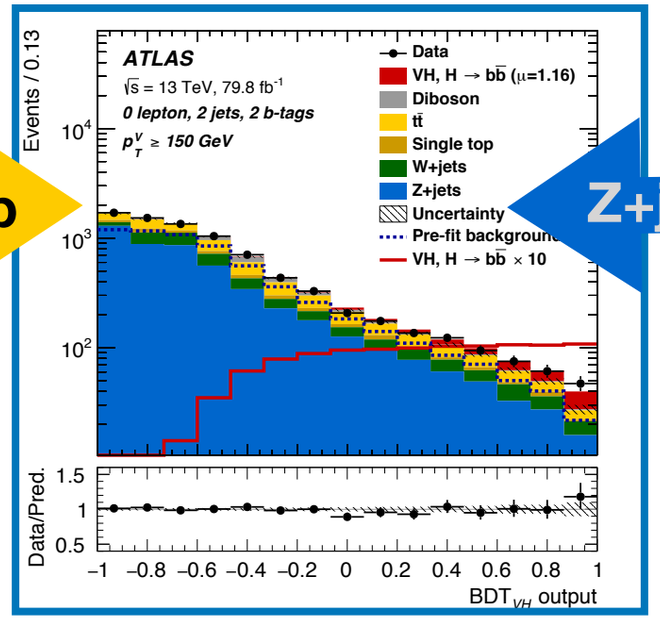
SRs

1-lepton



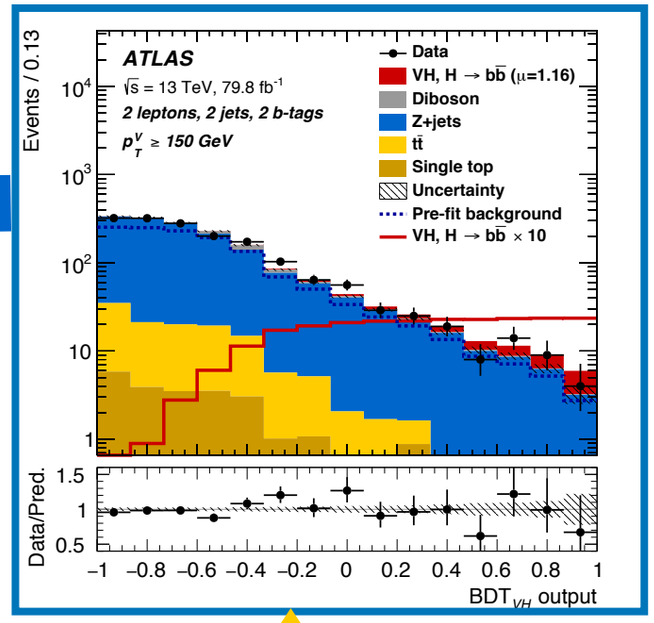
Top

0-lepton



Z+jets

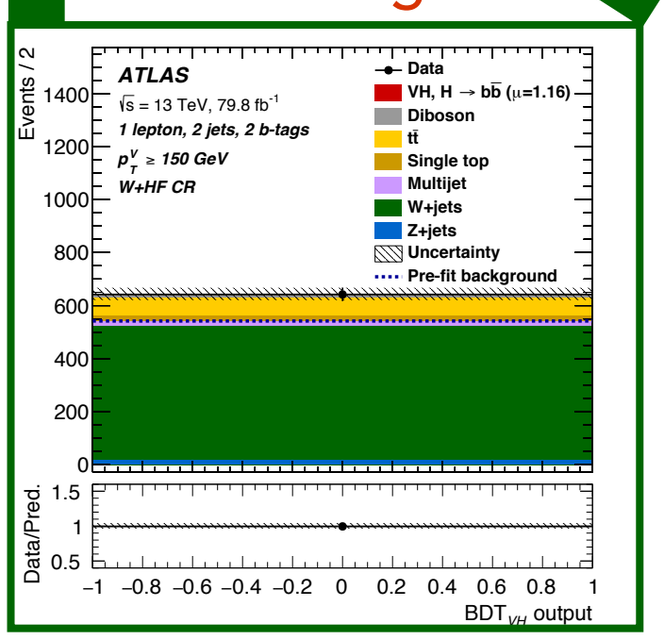
2-lepton



CRs

W+jets

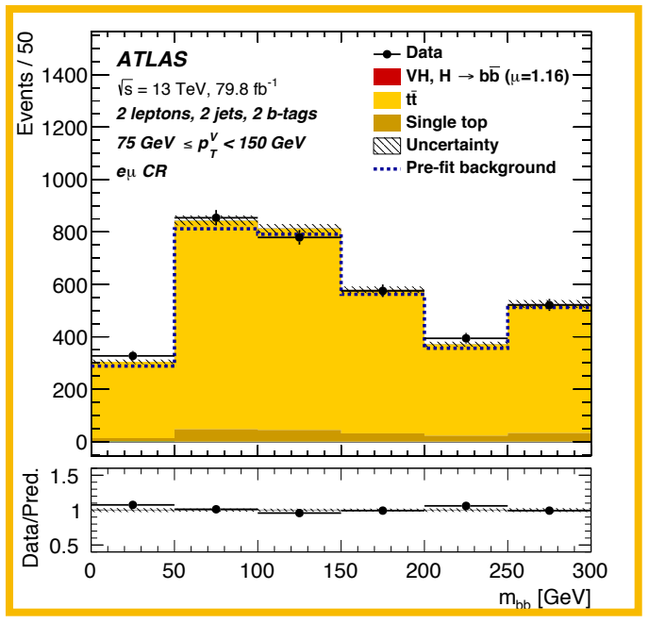
W+HF region



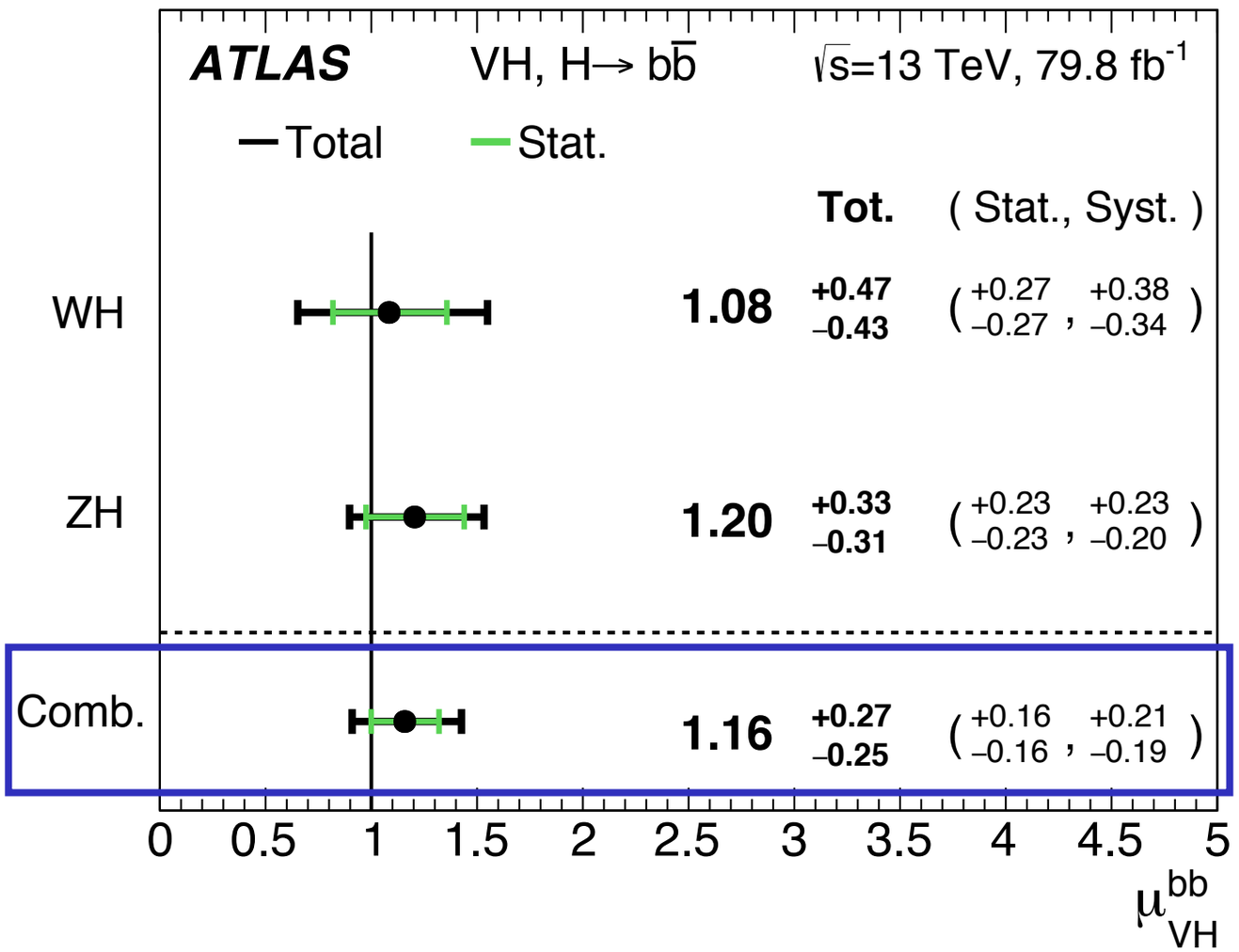
W+jets

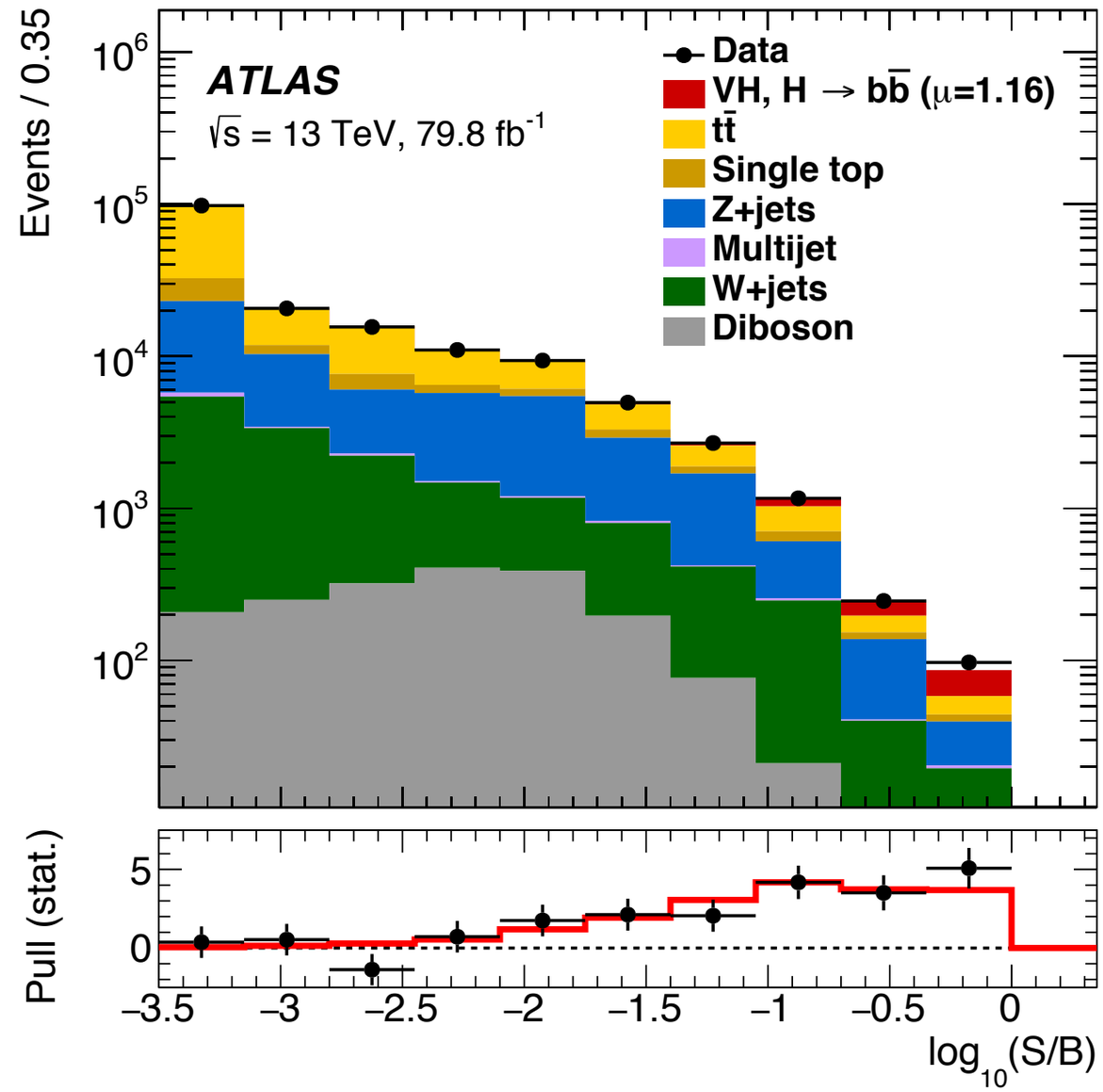
Top

eμ region



VH(H→bb) results





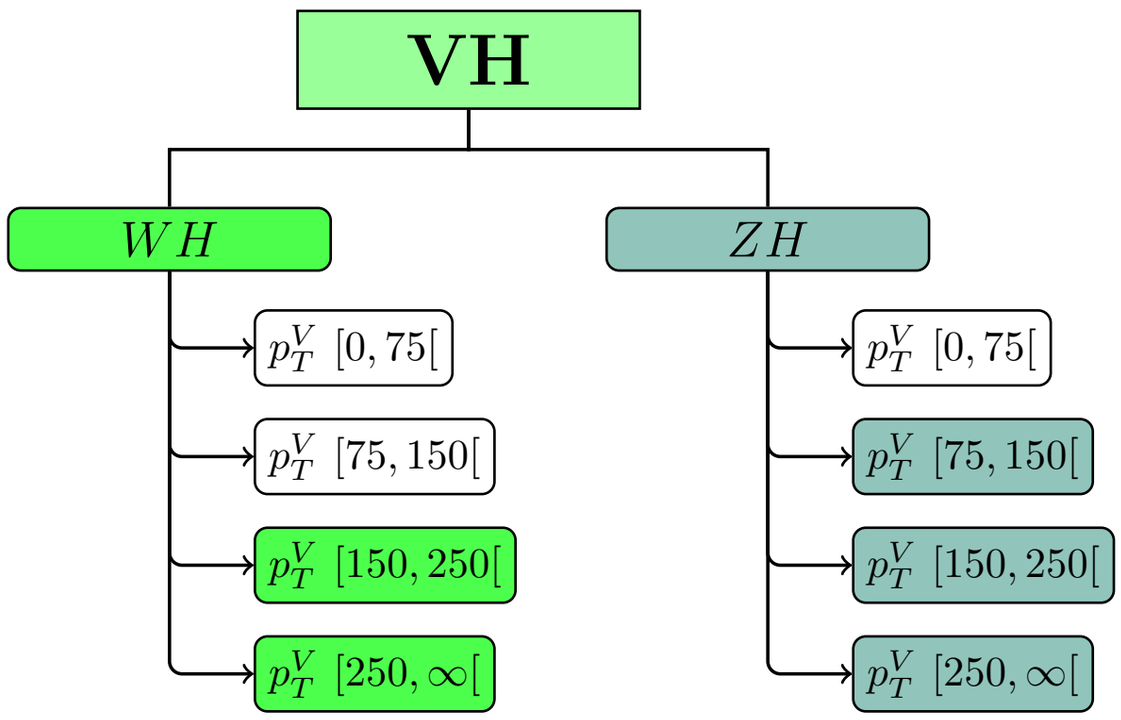
Signal strength μ compatible with the SM

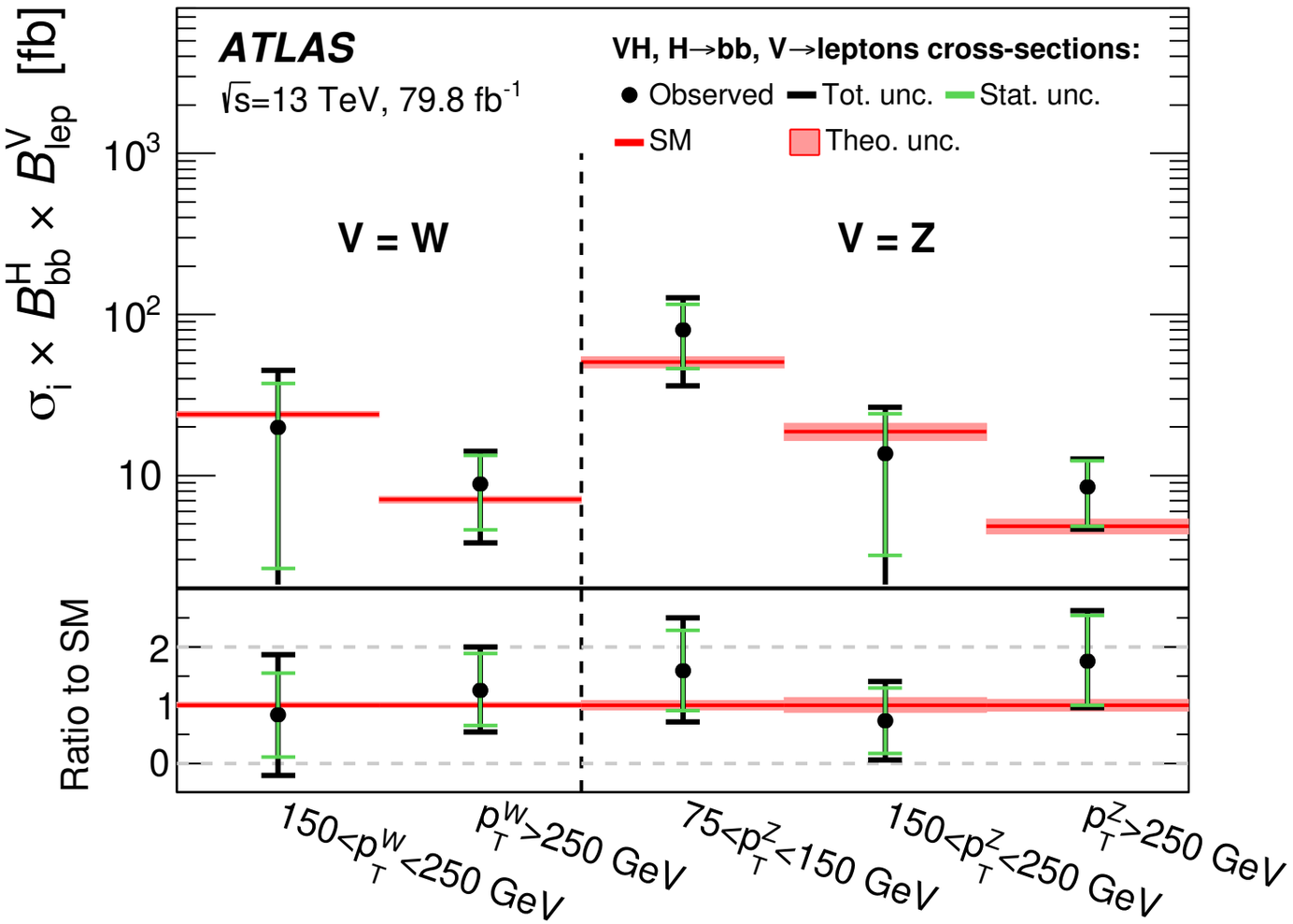
Significance of *VH(bb)* signal at 4.9**σ** (4.3**σ** expected)

Run1+Run2 in *VH*, ggF+VBF, *ttH* : observation *H→bb* decays at 5.4**σ** (5.5**σ** exp.)

Run 2 in *bb*, **γγ**, 4l decays : observation of *VH* production at 5.3**σ** (4.8**σ** exp.)

VH(H→bb) Cross Section measurements





- Beyond a single number: **cross section measurements**
- Production cross sections times branching ratio measured in mutually exclusive phase space regions (production bins)
- Sensitivity provided by **p_T^V analysis regions** and **BDT shapes**
- Targeting categories where higher **BSM** contributions expected
- Dedicated assessment of theory systematics wrt observation

Effective Field Theory

Use *VH*(*H*→*bb*) cross section measurements to search for deviations from the Standard Model using an EFT approach

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

- SM Lagrangian extended by a set of **higher dimension operators**
- Terms suppressed by a larger power of high mass scale **Λ**
- Leading effects from dim-6 operators, small deviations from SM
- Operators can be constrained in **Higgs boson measurements**

Constraints on EFT coefficients

Can constrain CP even coefficients of operators which affect VH processes: c_{HW}, c_{HB}, c_W - c_B and c_d (SILH basis)

This operator affects $H \to bb$ partial width, thus c_d involved in modification of BR($H \to bb$)

Operators affecting couplings to W and Z, thus *VH* cross sections: c_{HW} and c_W contribute to *HWW* and *HZZ* vertices, c_{HB} and c_B to *HZZ* only

HEL operator	Coefficient
$\mathcal{O}_g = \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$	$\frac{c_g}{\Lambda^2} = \frac{g_s^2}{m_W^2}\mathtt{cG}$
$\tilde{\mathcal{O}}_g = \lvert H\rvert^2 G^A_{\mu\nu} \tilde{G}^{A\mu\nu}$	$\frac{\tilde{c}_g}{\Lambda^2} = \frac{g_s^2}{m_W^2}\mathtt{tcG}$
$\mathcal{O}_\gamma = \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\frac{c_\gamma}{\Lambda^2} = \frac{g'^2}{m_W^2}\mathtt{cA}$
$\tilde{\mathcal{O}}_\gamma = \lvert H\rvert^2 B_{\mu\nu} \tilde{B}^{\mu\nu}$	$\frac{\tilde{c}_\gamma}{\Lambda^2} = \frac{g'^2}{m_W^2}\mathtt{tcA}$
$\mathcal{O}_u = y_u \lvert H\rvert^2 \bar{Q}_L H^\dagger u_R + \text{h.c.}$	$\frac{c_u}{\Lambda^2} = \frac{\mathtt{cu}}{v^2}$
$\mathcal{O}_d = y_d \lvert H\rvert^2 \bar{Q}_L H d_R + \text{h.c.}$	$\frac{c_d}{\Lambda^2} = \frac{\mathtt{cd}}{v^2}$
$\mathcal{O}_\ell = y_\ell \lvert H\rvert^2 \bar{L}_L H \ell_R + \text{h.c.}$	$\frac{c_\ell}{\Lambda^2} = \frac{\mathtt{cl}}{v^2}$
$\mathcal{O}_H = \frac{1}{2}\left(\partial^\mu \lvert H\rvert^2\right)^2$	$\frac{c_H}{\Lambda^2} = \frac{\mathtt{cH}}{v^2}$
$\mathcal{O}_6 = \left(H^\dagger H\right)^3$	$\frac{c_6}{\Lambda^2} = \frac{\lambda}{v^2}\mathtt{c6}$
$\mathcal{O}_{HW} = i\left(D^\mu H\right)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\frac{c_{HW}}{\Lambda^2} = \frac{g}{m_W^2}\mathtt{cHW}$
$\tilde{\mathcal{O}}_{HW} = i\left(D^\mu H\right)^\dagger \sigma^a (D^\nu H) \tilde{W}^a_{\mu\nu}$	$\frac{\tilde{c}_{HW}}{\Lambda^2} = \frac{g}{m_W^2}\mathtt{tcHW}$
$\mathcal{O}_{HB} = i\left(D^\mu H\right)^\dagger (D^\nu H) B_{\mu\nu}$	$\frac{c_{HB}}{\Lambda^2} = \frac{g'}{m_W^2}\mathtt{cHB}$
$\tilde{\mathcal{O}}_{HB} = i\left(D^\mu H\right)^\dagger (D^\nu H) \tilde{B}_{\mu\nu}$	$\frac{\tilde{c}_{HB}}{\Lambda^2} = \frac{g'}{m_W^2}\mathtt{tcHB}$
$\mathcal{O}_W = \frac{i}{2}\left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$	$\frac{c_W}{\Lambda^2} = \frac{g}{m_W^2}\mathtt{cWW}$
$\mathcal{O}_B = \frac{i}{2}\left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$	$\frac{c_B}{\Lambda^2} = \frac{g'}{m_W^2}\mathtt{cB}$

Effective Lagrangian Parametrisation

$$\sigma = \sigma_{SM} + \sigma_{int} + \sigma_{BSM}$$

int = SM-BSM interference

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i A_i \bar{c}_i + \sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$$

Linear terms

Cross section region	$\sum_i A_i \bar{c}_i$
$q\bar{q} \to Hl\nu$ $(150 \leq p_T^V \leq 250)$ GeV	50cHW + 74cWW
$q\bar{q} \to Hl\nu$ $(p_T^V \geq 250)$ GeV	170cHW + 200cWW
$q\bar{q} \to Hll$ $(75 \leq p_T^V \leq 150)$ GeV	13cHW + 38cWW + 3.9cHB + 10.5cB
$q\bar{q} \to Hll$ $(150 \leq p_T^V \leq 250)$ GeV	37cHW + 61cWW + 11cHB + 18cB
$q\bar{q} \to Hll$ $(p_T^V \geq 250)$ GeV	130cHW + 150cWW + 38cHB + 46cB

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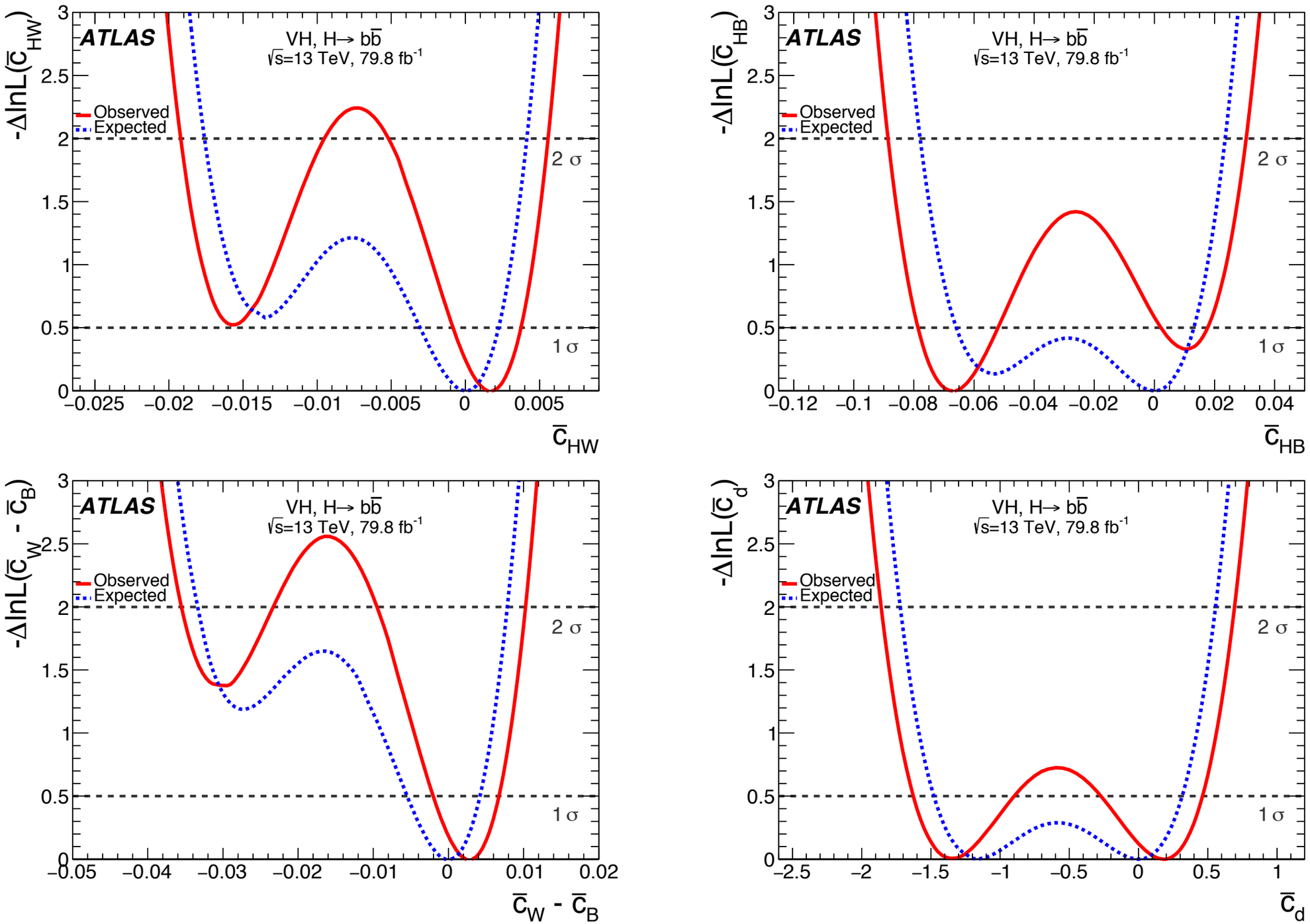
Quadratic terms

Cross section region	$\sum_{ij} B_{ij} \bar{c}_i \bar{c}_j$
$q\bar{q} \to Hl\nu$ $(150 \leq p_T^V \leq 250)$ GeV	839cHW^2 + 1555cWW^2 + cHW(900cWW)
$q\bar{q} \to Hl\nu$ $(p_T^V \geq 250)$ GeV	14000cHW^2 + 16000cWW^2 + cHW(30000cWW)
$q\bar{q} \to Hll$ $(75 \leq p_T^V \leq 150)$ GeV	85cHW^2 + 400cWW^2 + 8cHB^2 + 35cB^2
	+cHW(150cWW + 20cHB + 42cB)
	+cHB(44cWW + 12cB) + cWW(140cB)
$q\bar{q} \to Hll$ $(150 \leq p_T^V \leq 250)$ GeV	462cHW^2 + 982cWW^2 + 41cHB^2 + 86cB^2
	+cHW(1255cWW + 277cHB + 358cB)
	+cHB(373cWW + 105cB) + cWW(587cB)
$q\bar{q} \to Hll$ $(p_T^V \geq 250)$ GeV	8000cHW^2 + 9600cWW^2 + 720cHB^2 + 850cB^2
	+cHW(17000cWW + 4800cHB + 5100cB)
	+cHB(5100cWW + 1500cB) + cWW(5700cB)

Linear+Quadratic Contribution

Simultaneous maximum-likelihood fit to the production bins

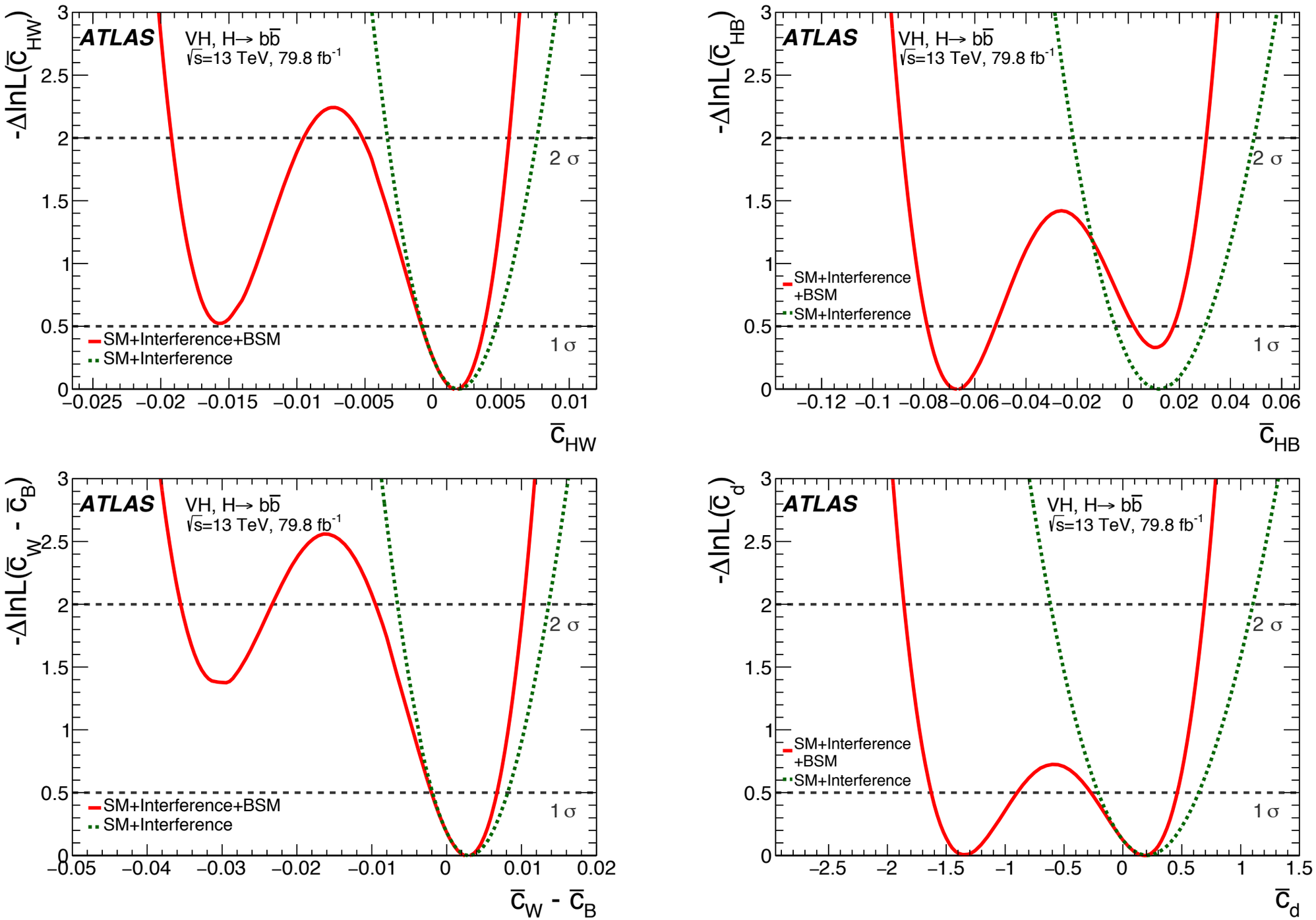
Fit performed in one dimension for each EFT coefficient (others kept at 0)



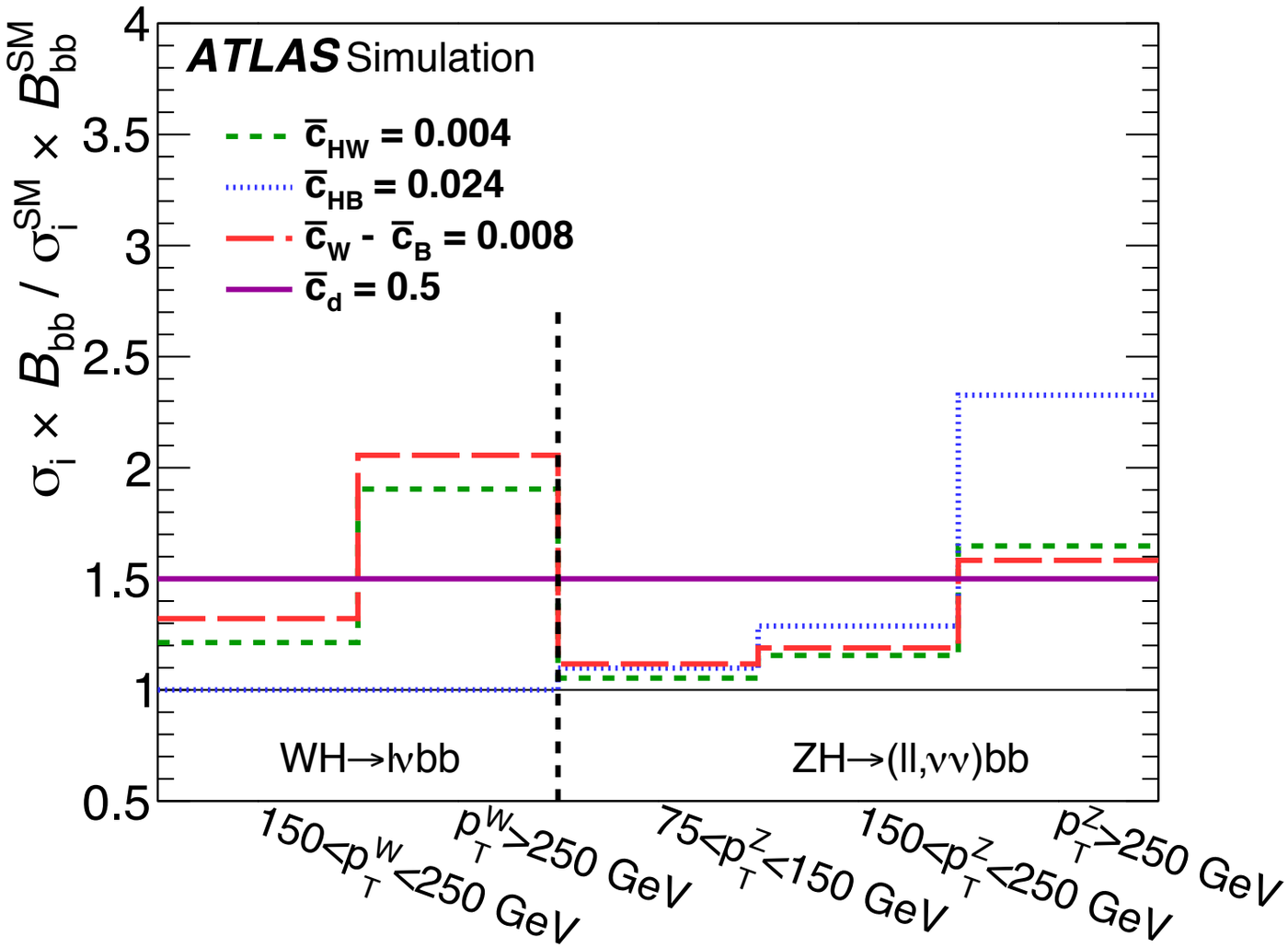
Only Linear vs Full Contribution

Linear+Quadratic has two minima due to parabolic parametrisation

"Only linear" has single minimum structure since it is monotonic



Summary



- Observation of *VH* production and *bb* decays
- Production cross section measurements (finer granularity)
- Constraints on EFT coefficients affecting VH production (c_{HW}, c_{HB}, c_W-c_B)
- New coefficient c_d, which only affects decay, constrained
- Will serve as input for the ATLAS Global EFT Fit

Effect of the EFT coefficients on the cross sections, assuming the upper limit at 95% CL as value for coefficients

Results published in
Phys. Lett. B 786 (2018) 59
JHEP05 (2019) 141

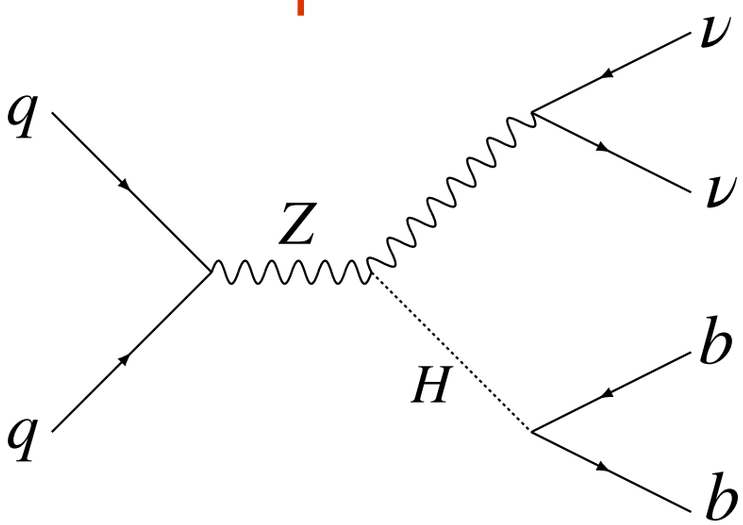
Thank you!

Additional Material

Event Selection for *VH(H→bb)*

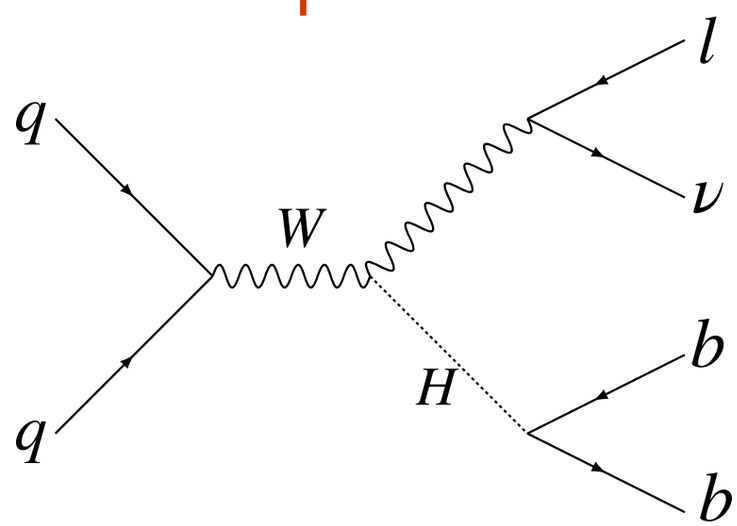
- Leptonic decays of *Z/W*: efficient triggering and bkg rejection
- 3 channels according to the number of leptons (0, 1, 2)
- Exactly 2 *b*-tagged jets with 0 or 1 additional jet

0-lepton



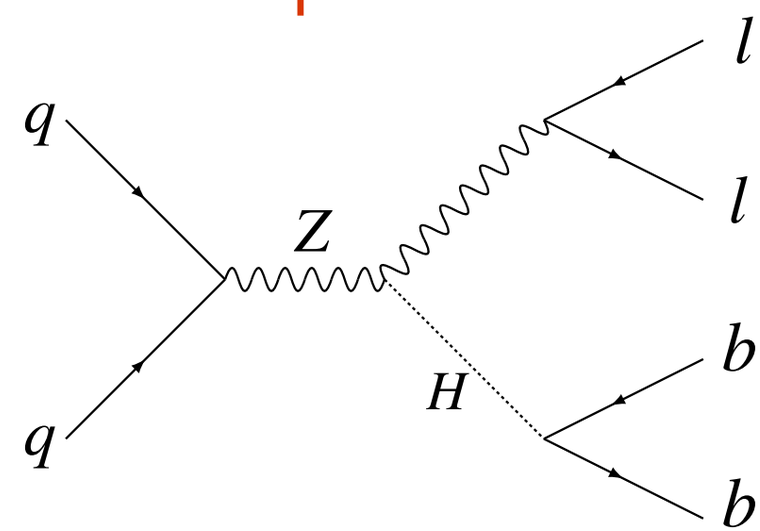
- E_T^{miss} trigger
- Veto leptons $p_T > 7$ GeV
- $p_T^{Z}(E_T^{miss}) > 150$ GeV

1-lepton



- Electron or E_T^{miss} trigger
- One isolated lepton
- $p_T > 25$ (27) GeV for μ (e)
- $p_T^{W}(l,\nu) > 150$ GeV

2-lepton



- Single-lepton trigger
- 2 *e* or μ $p_T > 27$ (7) GeV
- $p_T^{Z}(l,l)$ [75-150 GeV] or >150 GeV

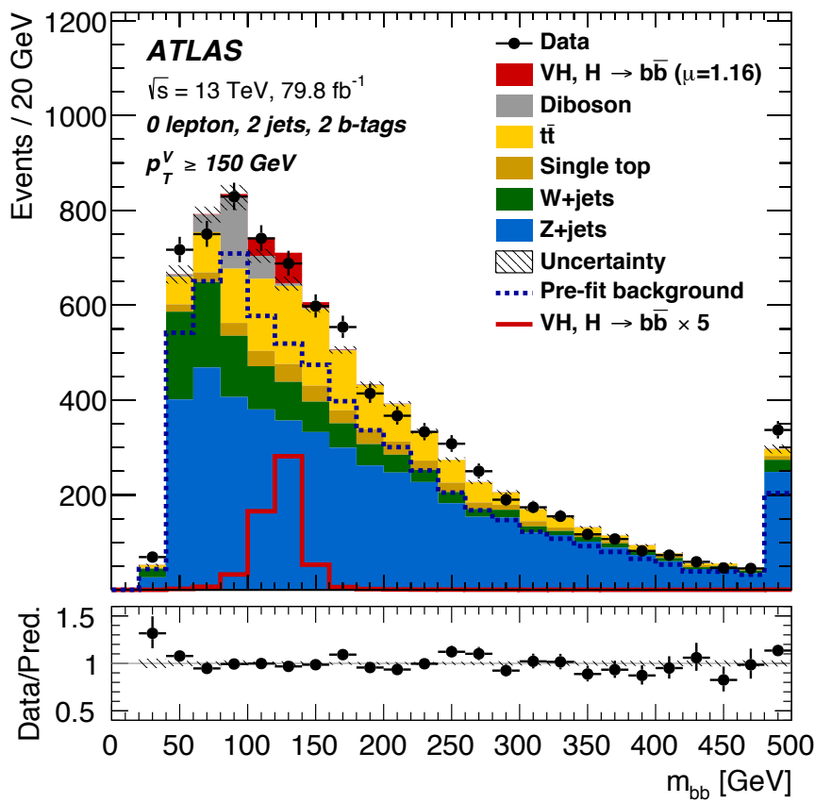
Define several categories based on the number of leptons, number of jets and p_T^V

Complete Event Selection

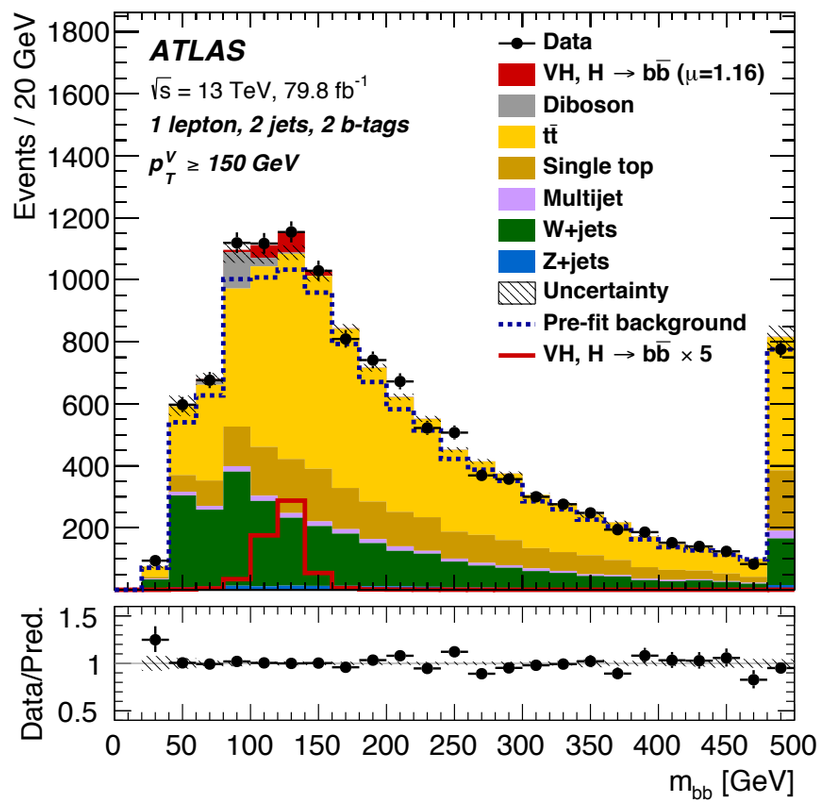
Selection	0-lepton	1-lepton		2-lepton
		e sub-channel	μ sub-channel	
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV	1 *tight* electron $p_{\mathrm{T}} > 27$ GeV	1 *tight* muon $p_{\mathrm{T}} > 25$ GeV	2 *loose* leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		81 GeV $< m_{\ell\ell} <$ 101 GeV
Jets	Exactly 2 / Exactly 3 jets			Exactly 2 / ≥ 3 jets
Jet p_{T}	> 20 GeV for $\lvert\eta\rvert < 2.5$ > 30 GeV for $2.5 < \lvert\eta\rvert < 4.5$			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
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			75 GeV $< p_{\mathrm{T}}^{V} <$ 150 GeV, > 150 GeV
Signal regions	–	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charges ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons Opposite-sign charges

Background Modelling

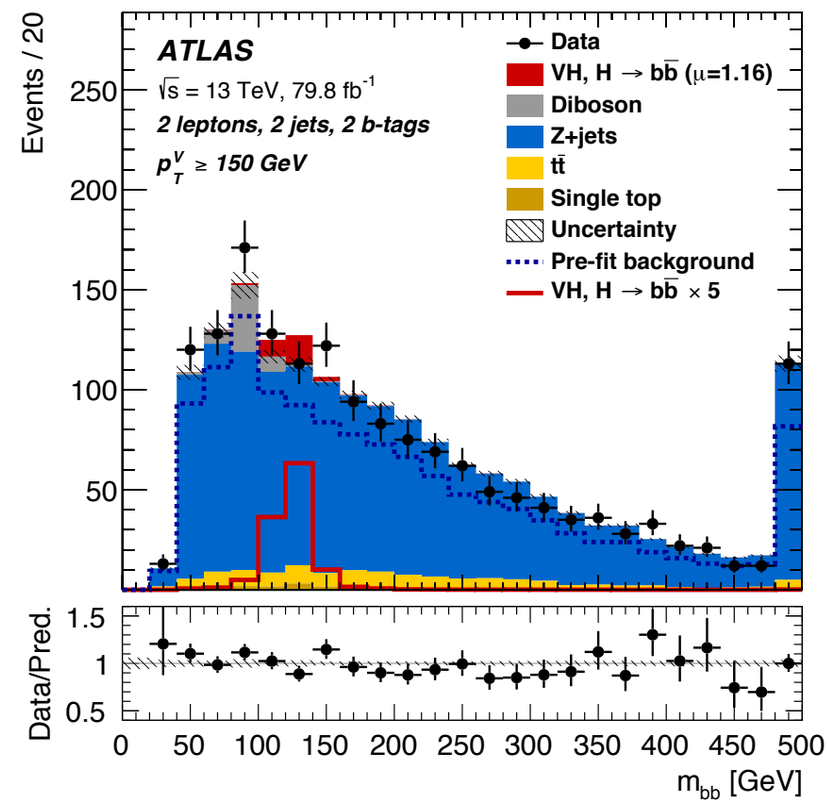
0-lepton



1-lepton



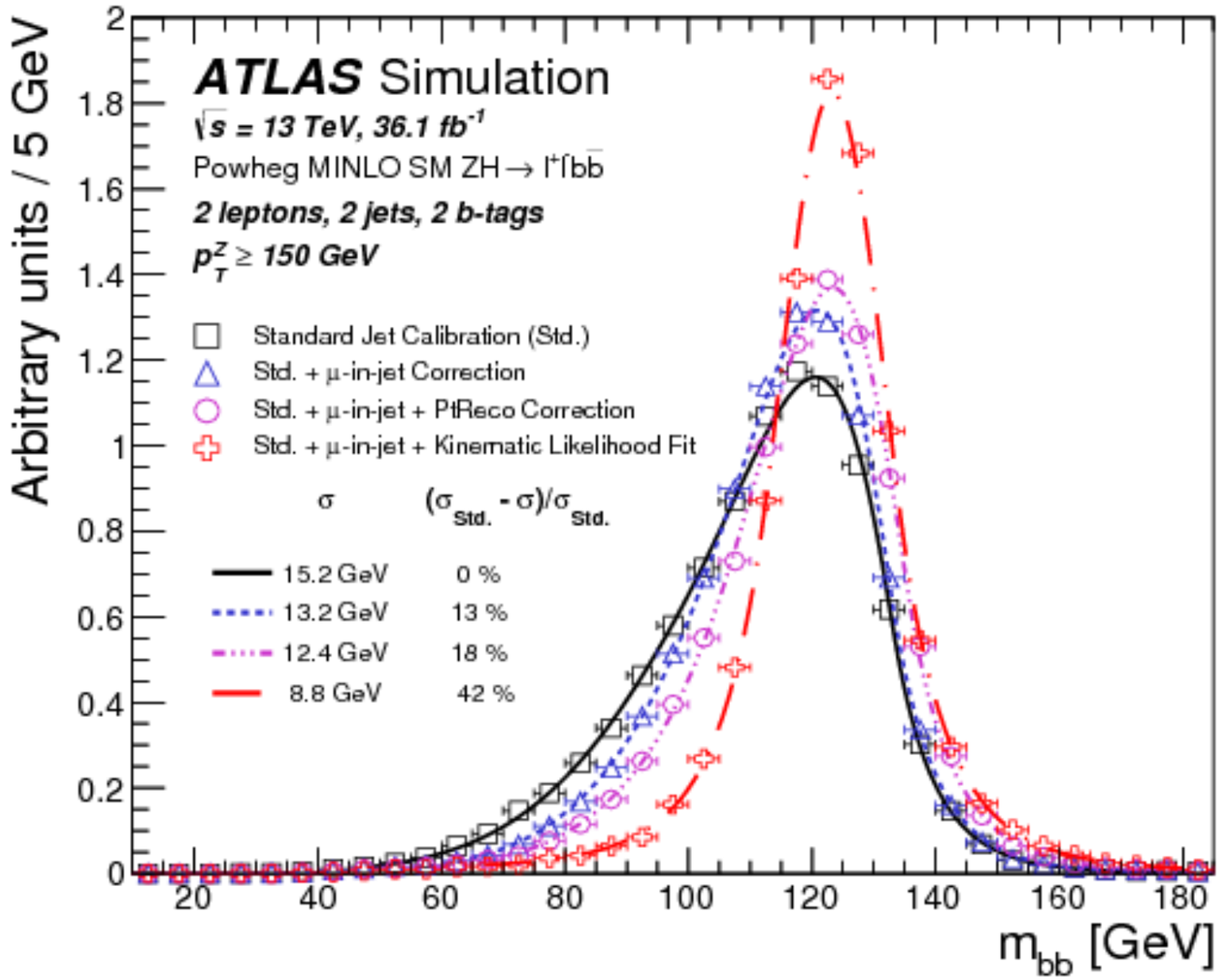
2-lepton



VH, H→bb	Signal (Powheg+Pythia8)
Z+jets and **W+jets**	*W*/*Z* bosons associated with jets (Sherpa)
$t\bar{t}$ and **Single top**	top quark pairs and single top (Powheg+Pythia8)
Diboson	vector boson pairs (Sherpa)
Multijet	QCD multi-*b*-jets (data-driven estimation)

b-jet corrections

Consecutive corrections to improve mass resolution



Muon-in-jet add muons in the vicinity of the jet

p_T reco allows to recover the energy of neutrinos

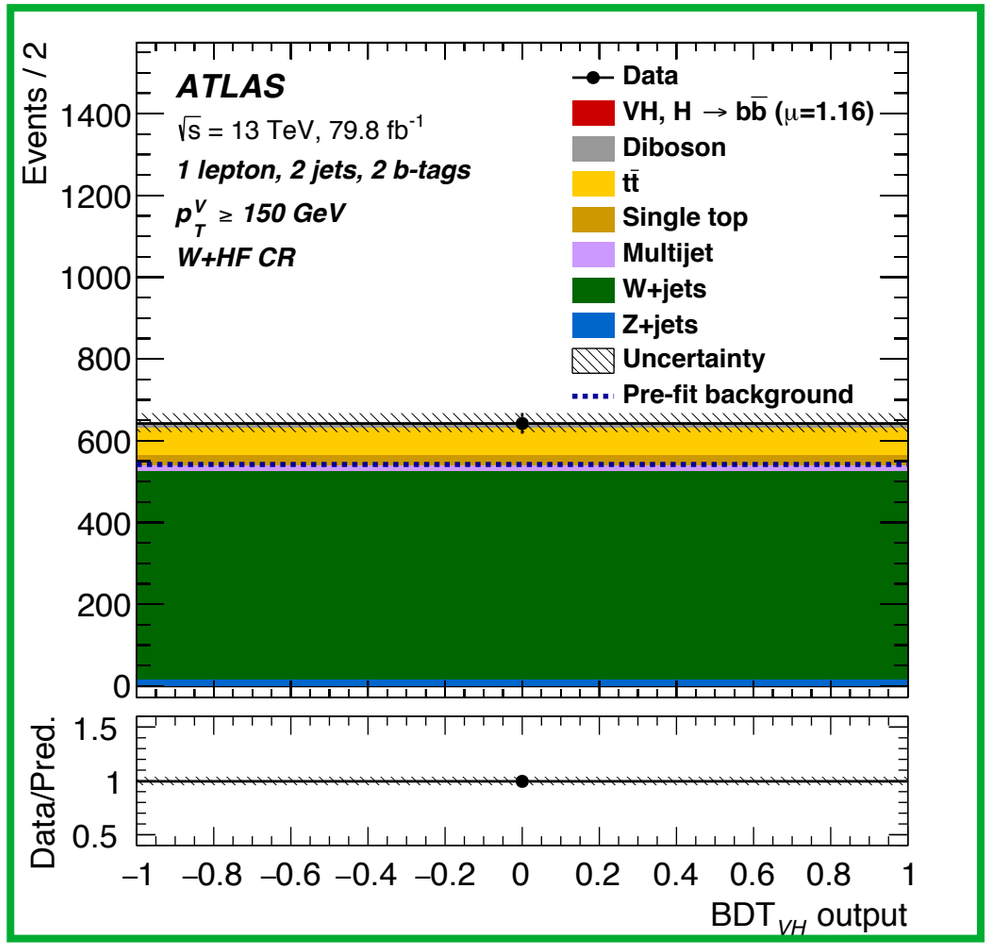
Kinematic likelihood fit in 2 lepton channel to constrain the *llbb* system

Multivariate Analysis (MVA)

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

- Discrimination between signal and background increased by a **MVA**
- **Boosted Decision Tree** (BDT) trained separately for each category
- Observables combined into the BDT: m_{bb}, ΔR_{bb}, p_T^V most important

W+HF Control Region



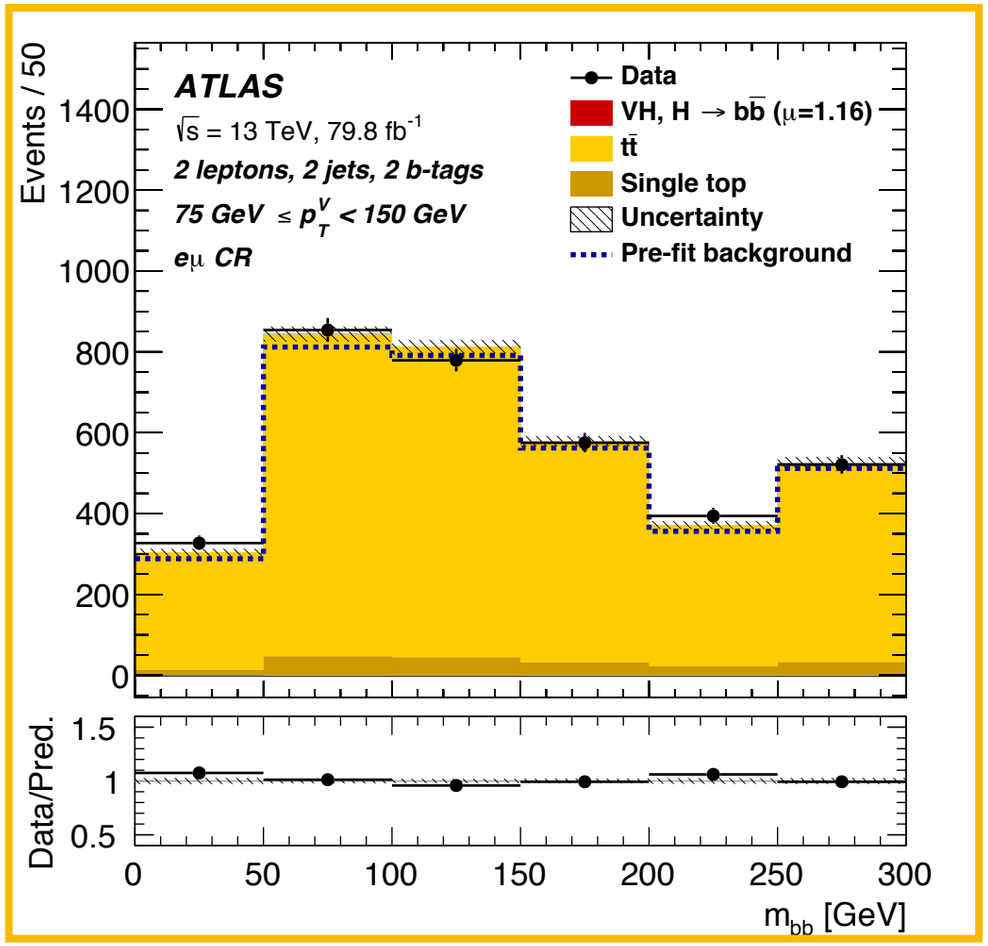
CRs are orthogonal to the signal regions, with negligible level of signal contamination

- 1-lepton CR (2 jets and 3 jets)
- ~75% purity

Variable	Cut
m_{top}	> 225 GeV
m_{bb}	< 75 GeV

- Reduces VH signal contamination
- Reduces ttbar and single-top

$e\mu$ Control Region



- 2-lepton CR (2 p_T^V regions for 2 jets and 3+ jets)
- ~99% purity

Selected by requiring same kinematic selection as signal region, but different flavour of a pair of dilepton (eμ or μe)

ttbar is flavour symmetric

Systematic Uncertainties

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
$E_{\mathrm{T}}^{\mathrm{miss}}$		0.014
Leptons		0.009
b-tagging	b-jets	0.061
	c-jets	0.042
	light-flavour jets	0.009
	extrapolation	0.008
Pile-up		0.007
Luminosity		0.023
Theoretical and modelling uncertainties		
Signal		0.094
Floating normalisations		0.035
Z + jets		0.055
W + jets		0.060
$t\bar{t}$		0.050
Single top quark		0.028
Diboson		0.054
Multi-jet		0.005
MC statistical		0.070

Analysis dominated by systematic uncertainties

b-tagging

both *b* (~3%) and *c* (~10%) tagging calibration

Background modelling

Z+HF, W+HF, ttbar

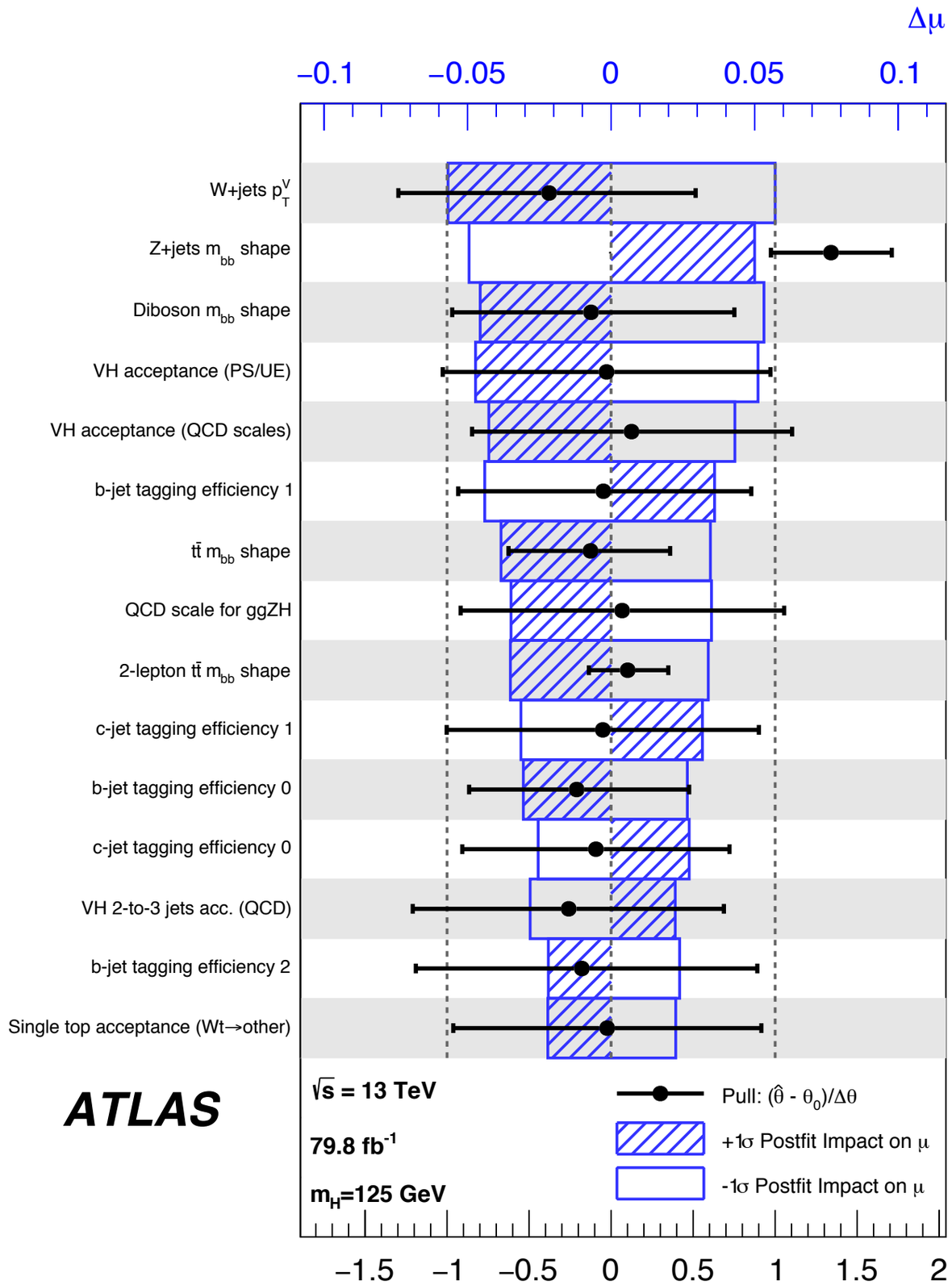
Signal modelling

Limited impact on significance

MC stats

Use of dedicated MC filters

Nuisance Parameter Ranking

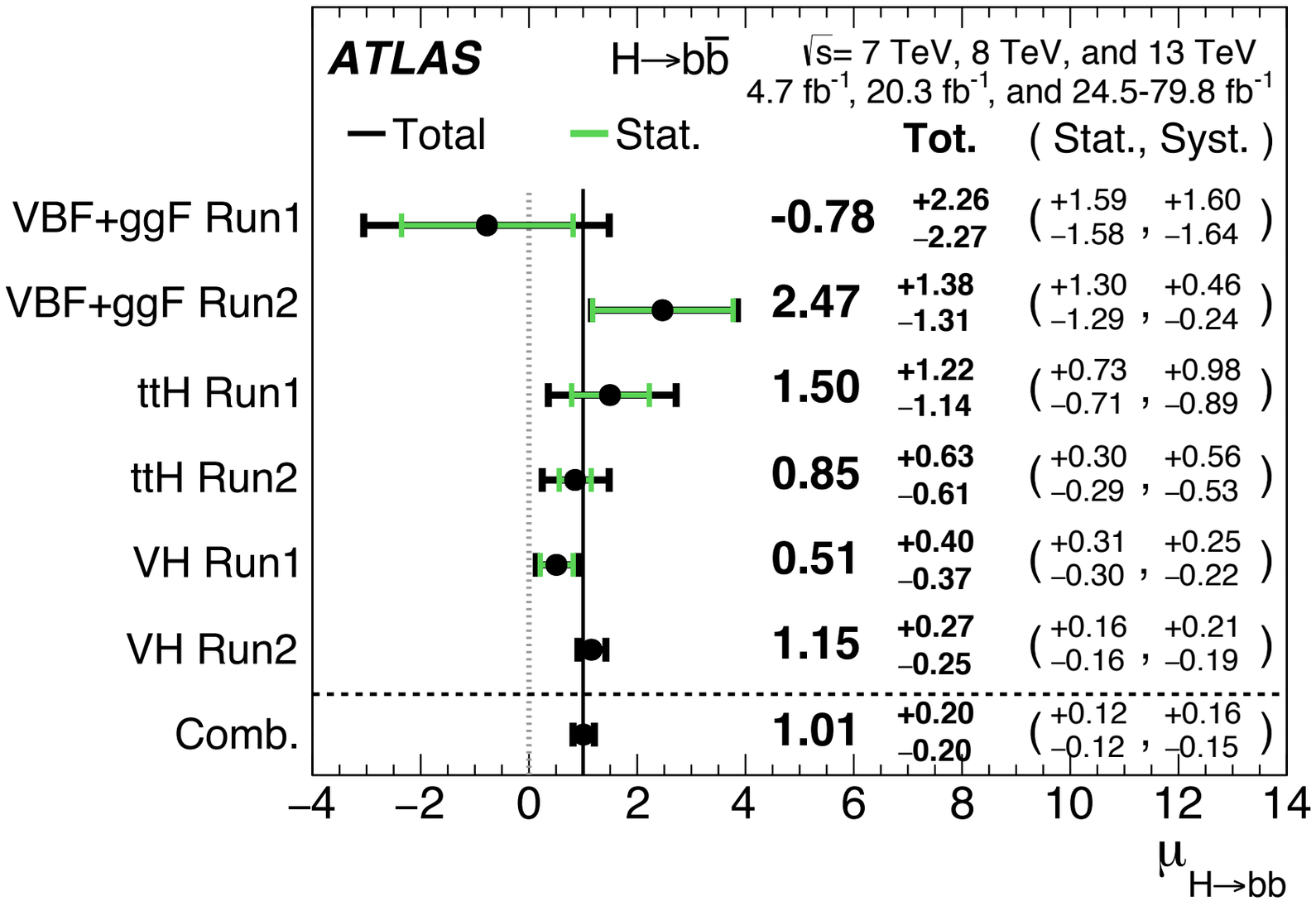


Statistical Analysis

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.98 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	1.06 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	0.95 ± 0.06
$W + \mathrm{HF}$ 2-jet	1.19 ± 0.12
$W + \mathrm{HF}$ 3-jet	1.05 ± 0.12
$Z + \mathrm{HF}$ 2-jet	1.37 ± 0.11
$Z + \mathrm{HF}$ 3-jet	1.09 ± 0.09

Factors applied to the nominal normalisations of the $t\bar{t}$, *W+HF* and *Z+HF* backgrounds, as obtained from the global likelihood fit to the 13 TeV data for the nominal multivariate analysis, used to extract the Higgs boson signal. The errors represent the combined statistical and systematic uncertainties.

H→bb Combination

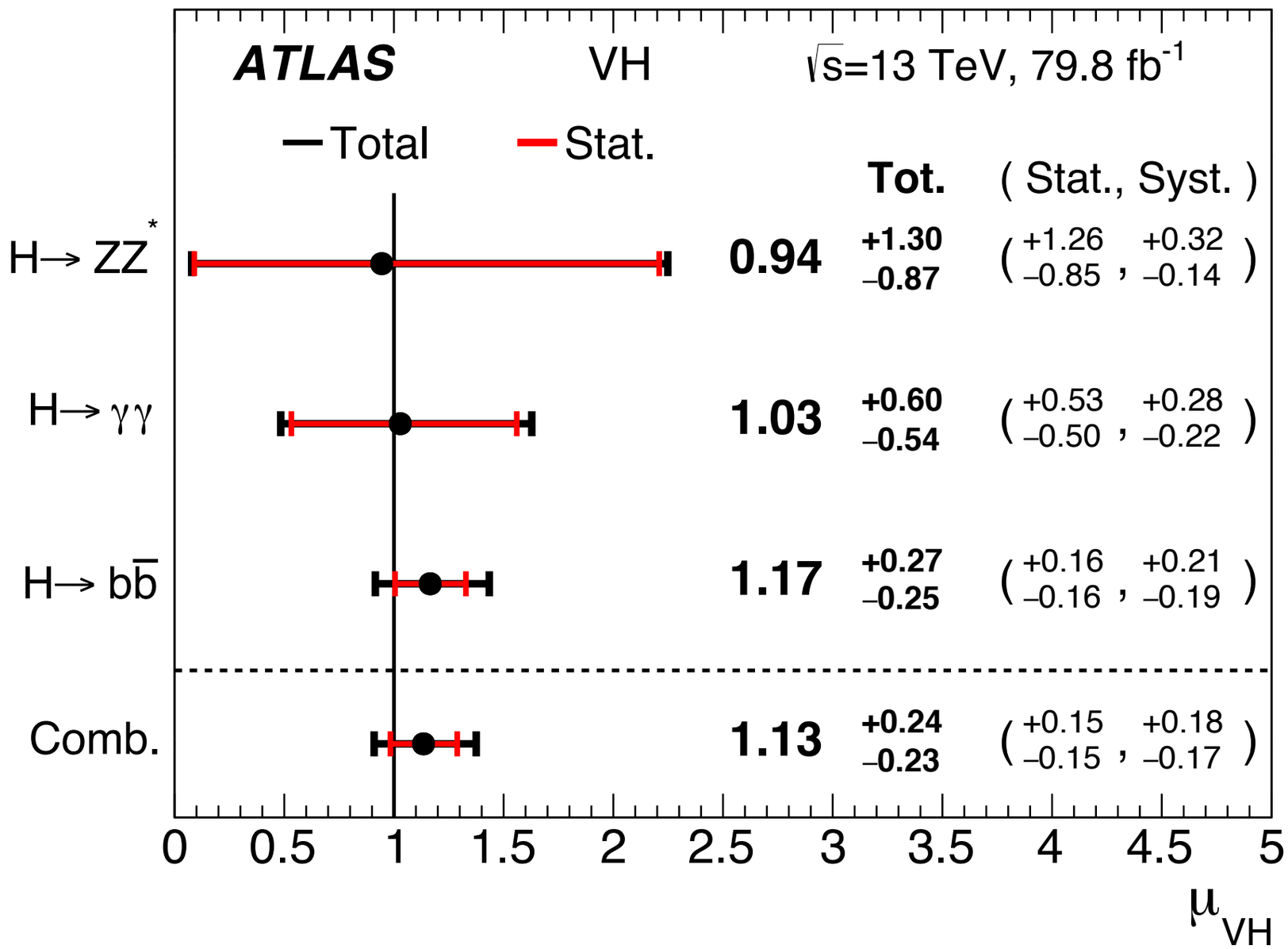


Run 1 and Run 2 analyses in *VH*, ggF, VBF and *ttH* production modes

Observation of *H→bb* decays at 5.4**σ** (5.5**σ** exp.)

VH channel main contribution

VH Combination



Run 2 analyses in *bb*, **γγ**, 4l decays

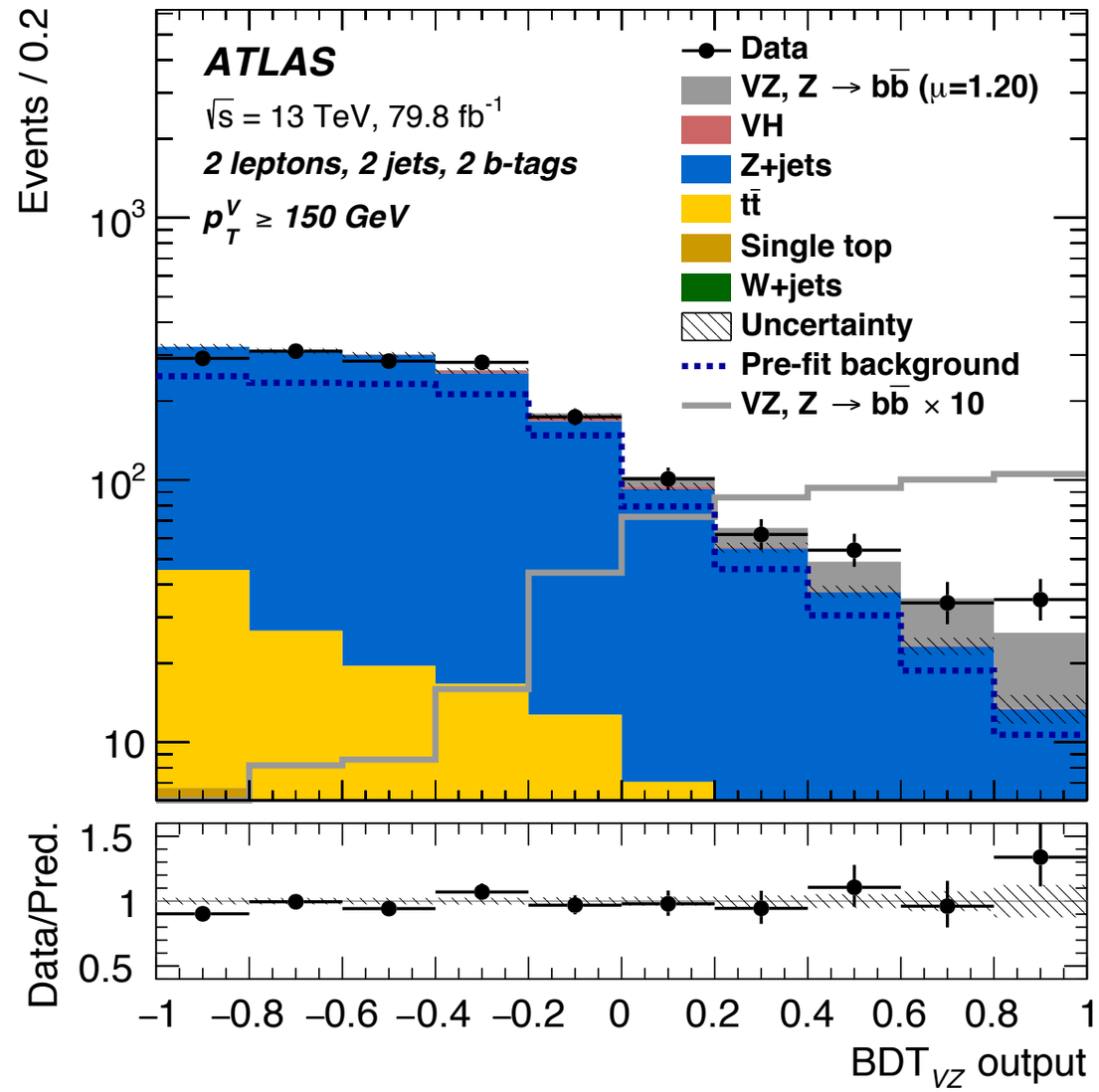
Observation of *VH* production at 5.3**σ** (4.8**σ** exp.)

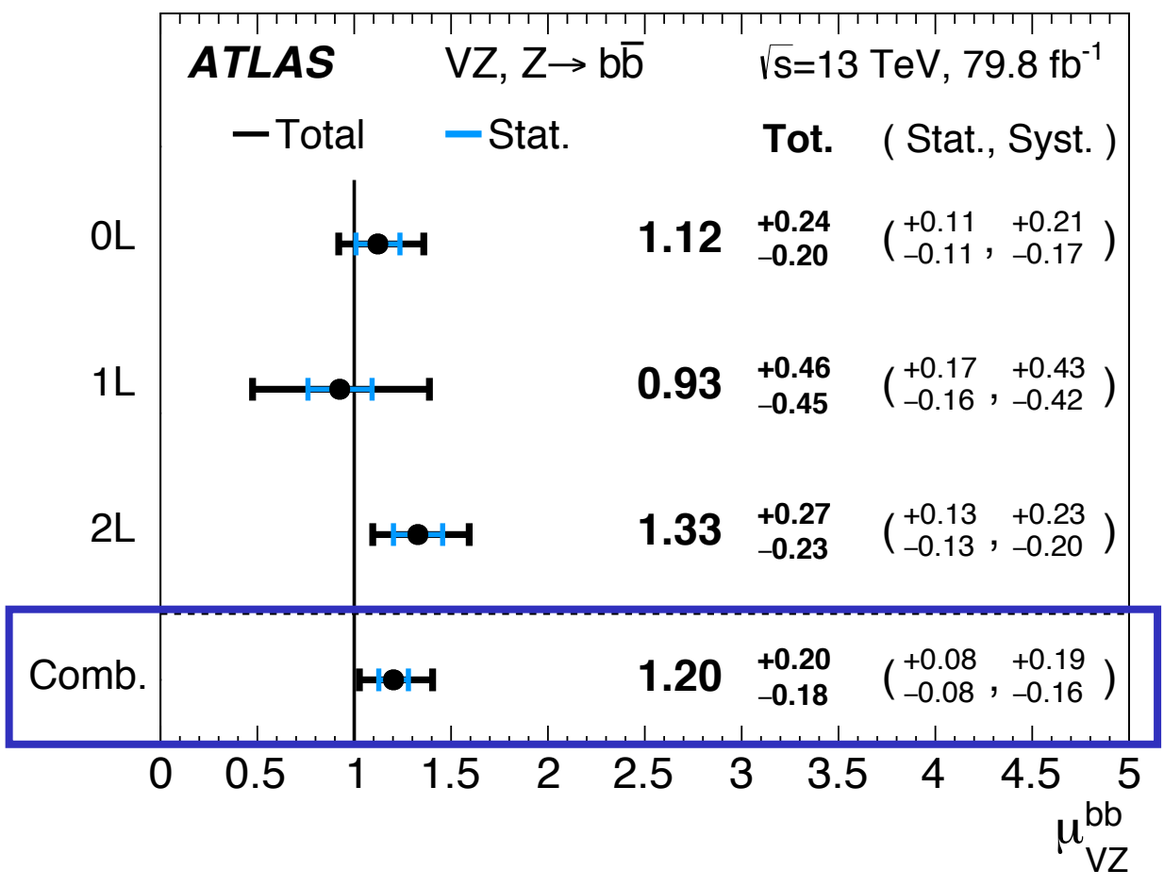
bb channel main contribution

Validation: Diboson MVA analysis

Analysis procedure validation

- Same selection as *VH*
- Retrain the BDT using:
  - *VZ*(*Z*→*bb*) as signal
  - Same bkg + *VH*
- Repeat the fit on BDT_{VZ} to extract *VZ*(*Z*→*bb*) signal strength



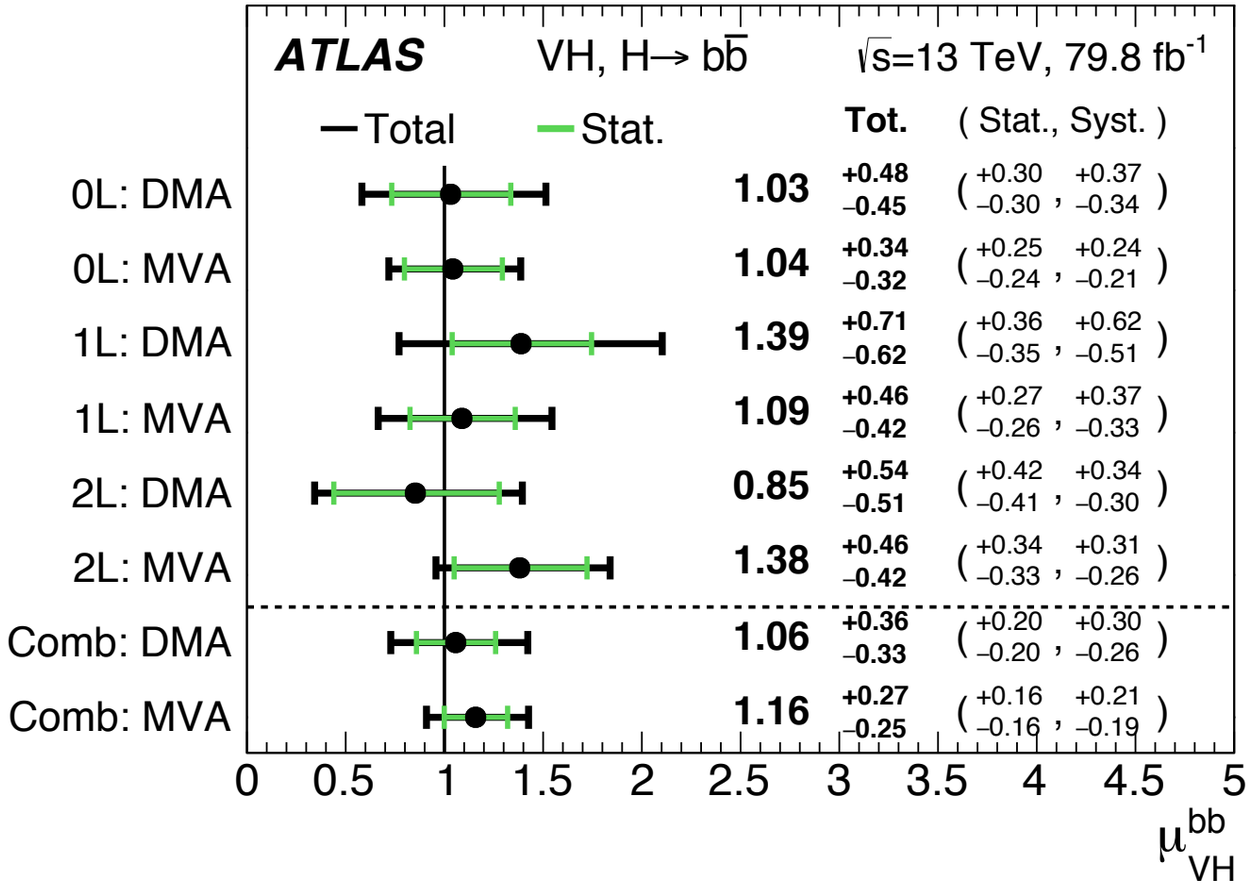


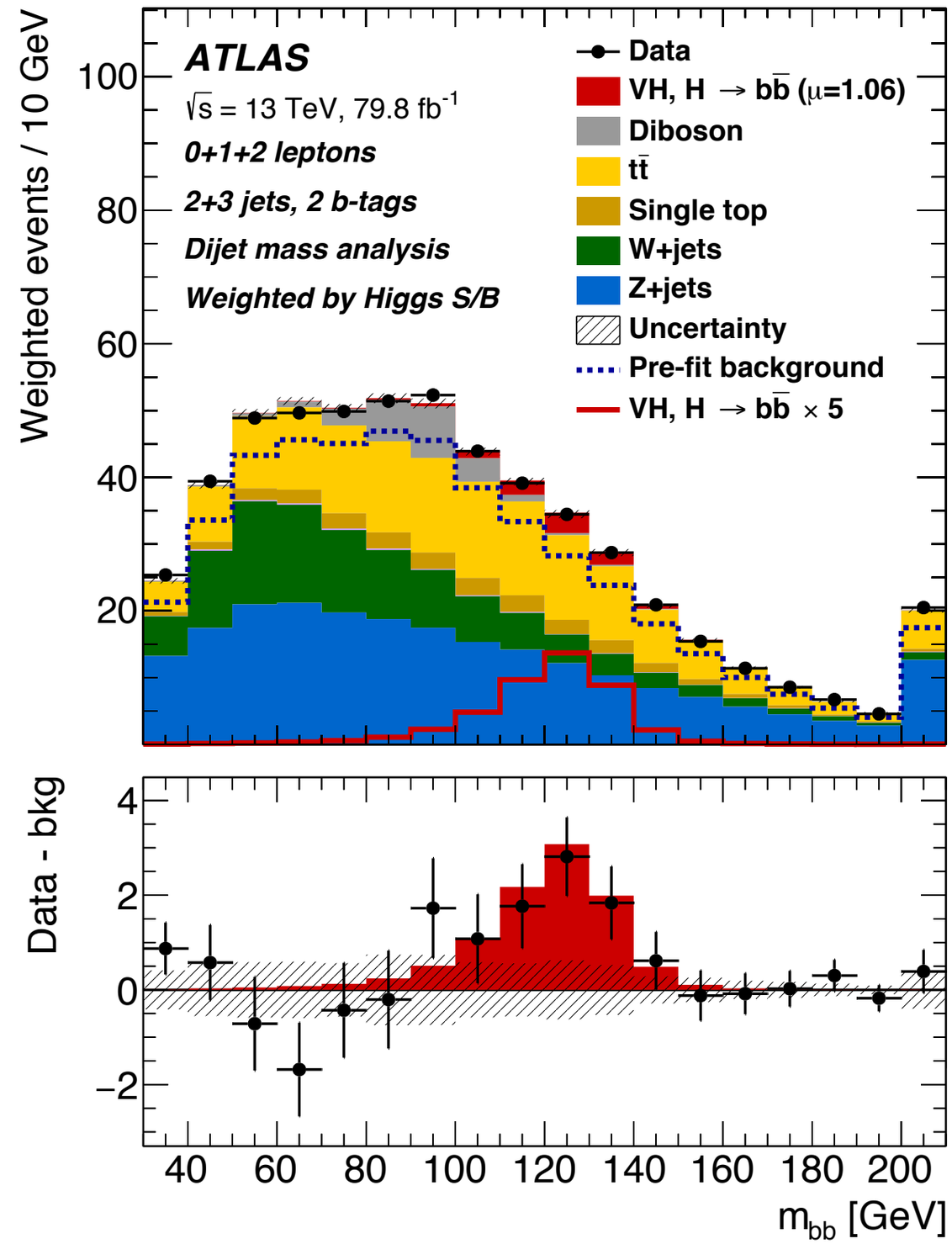
Significance of *VZ*(*Z*→*bb*) signal >> 5**σ**

Signal strength μ compatible with the SM

Cross Check: dijet analysis

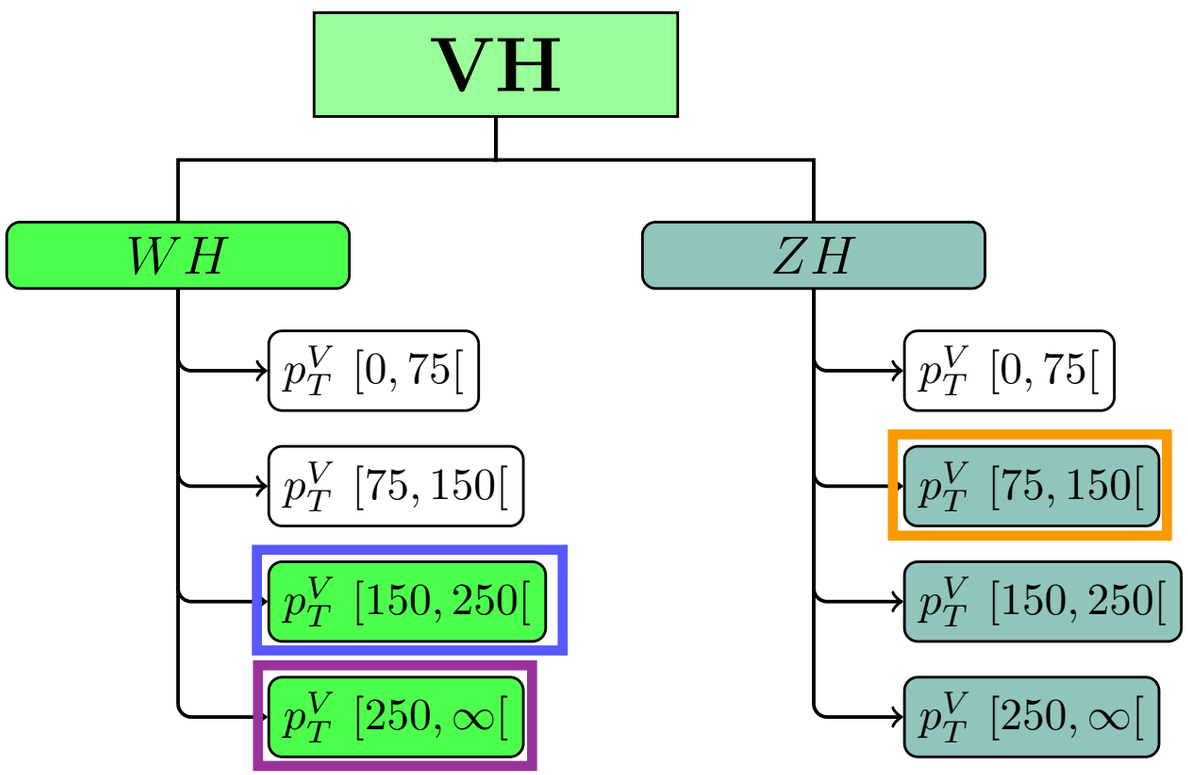
- Different strategy wrt MVA analysis: fit m_{bb} spectrum
- More p_T^V regions
- Additional cuts to suppress *V*+jets and *ttbar*
- Less sensitive than the MVA analysis (~27%)

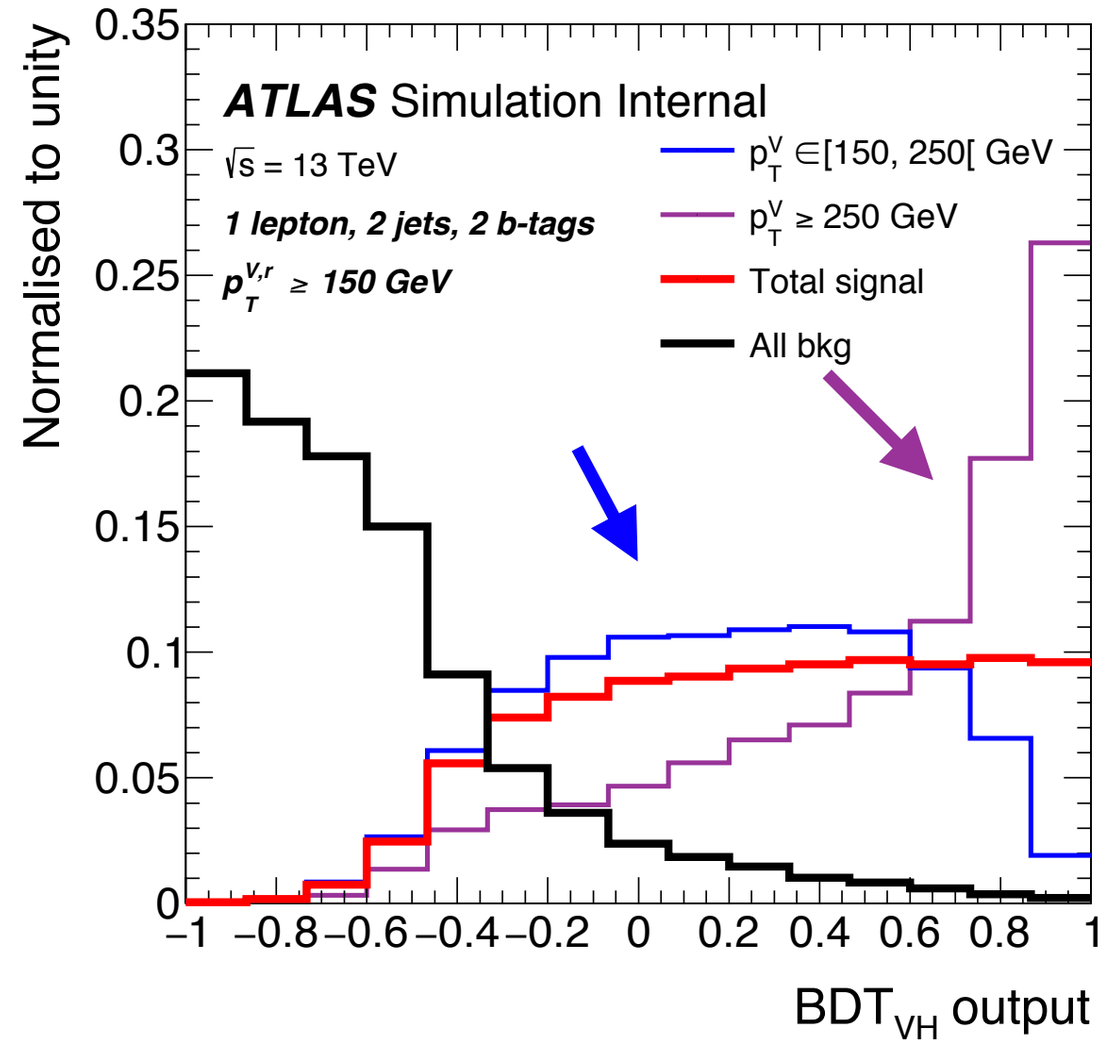




$VH(H \rightarrow bb)$ Cross Section measurements

5 STXS truth bins





Sensitivity to 75< p_T^Z <150 GeV is provided by the 2 lepton category

Reconstructed categories do not distinguish between events with true p_T^V below or above 250 GeV

Sensitivity to the two p_T^V regions 150-250 GeV and >250 GeV is provided by the different shapes of the BDT$_{VH}$ discriminant

Effective Field Theory Intervals

Coefficient	Expected interval	Observed interval
	Results at 68% confidence level	
$\bar{c}_{HW}$	[−0.003, 0.002]	[−0.001, 0.004]
(interference only	[−0.002, 0.003]	[−0.001, 0.005])
$\bar{c}_{HB}$	[−0.066, 0.013]	[−0.078, −0.055] $\bigcup$ [0.005, 0.019]
(interference only	[−0.016, 0.016]	[−0.005, 0.030])
$\bar{c}_W - \bar{c}_B$	[−0.006, 0.005]	[−0.002, 0.007]
(interference only	[−0.005, 0.005]	[−0.002, 0.008])
$\bar{c}_d$	[−1.5, 0.3]	[−1.6, −0.9] $\bigcup$ [−0.3, 0.4]
(interference only	[−0.4, 0.4]	[−0.2, 0.7])
	Results at 95% confidence level	
$\bar{c}_{HW}$	[−0.018, 0.004]	[−0.019,−0.010] $\bigcup$ [−0.005, 0.006]
(interference only	[−0.005, 0.005]	[−0.003, 0.008])
$\bar{c}_{HB}$	[−0.078, 0.024]	[−0.090, 0.032]
(interference only	[−0.033, 0.033]	[−0.022, 0.049])
$\bar{c}_W - \bar{c}_B$	[−0.034, 0.008]	[−0.036,−0.024] $\bigcup$ [−0.009, 0.010]
(interference only	[−0.009, 0.010]	[−0.006, 0.014])
$\bar{c}_d$	[−1.7, 0.5]	[−1.9, 0.7]
(interference only	[−0.8, 0.8]	[−0.6, 1.1])