Measurement of the VH, $H \rightarrow b\bar{b}$ production as a function of the vector boson transverse momentum in 13 TeV pp collisions with the ATLAS detector

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On behalf of the ATLAS Collaboration

Higgs Couplings

Oxford, 30th September – 4th October 2019

IN SUPREMÆ DIGNITATIS 1343

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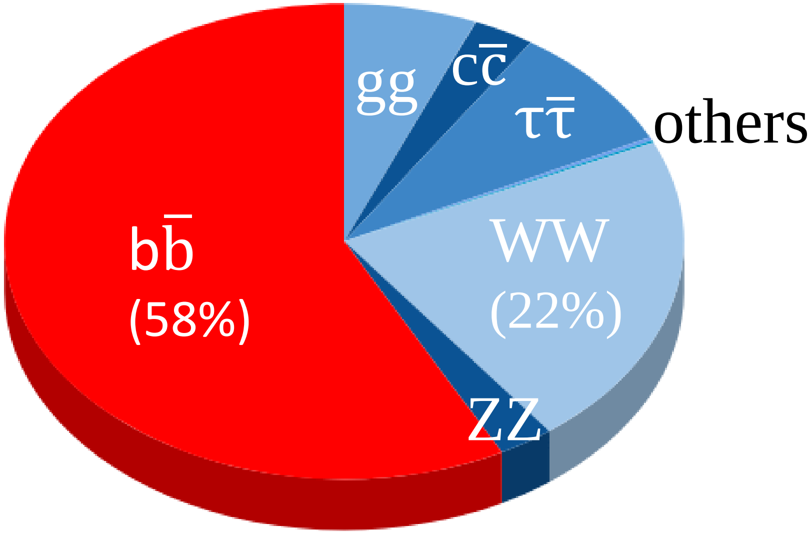
ATLAS EXPERIMENT

Outline

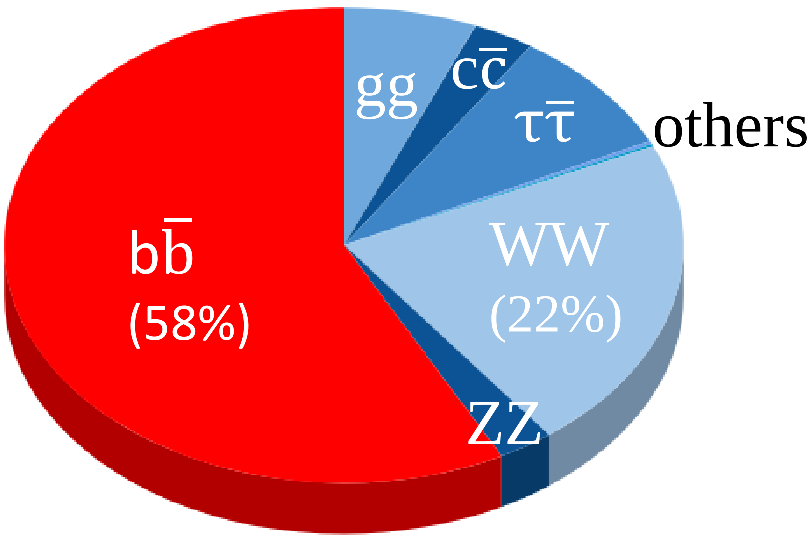
- Motivation for VH, $H\to b\bar{b}$ search
- Analysis strategy
- Results
- Differential pp $\to$VH cross section measurements
- Conclusions

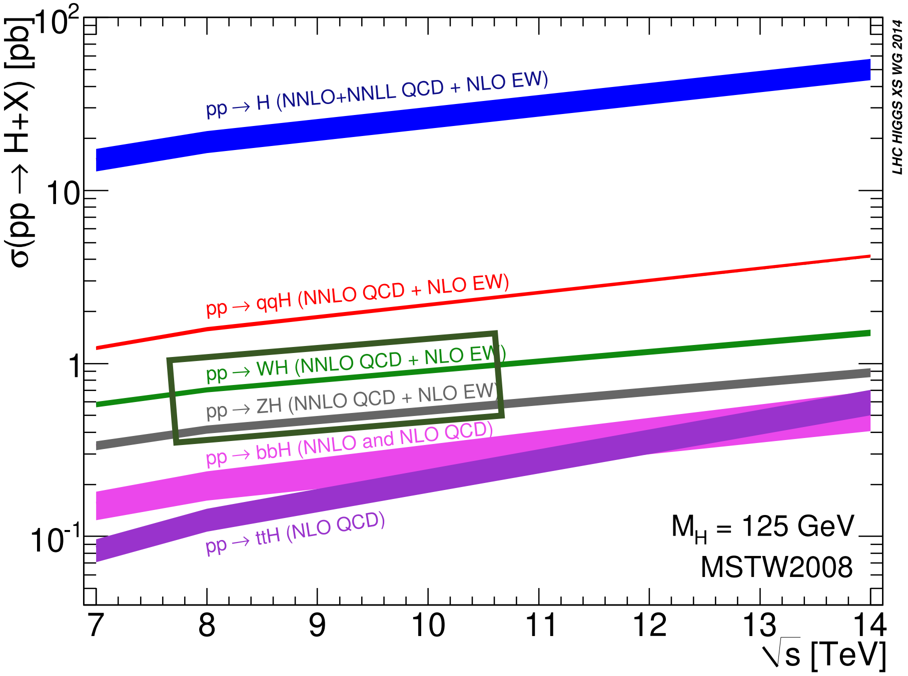
Why VH, H→$b\bar{b}$?



- Large BR (58%) *YR4, CERN-2017-002-M*
- Direct coupling between Higgs and quarks

Why VH, H→$b\bar{b}$?





- Large BR (58%) *YR4, CERN-2017-002-M*
- Direct coupling between Higgs and quarks

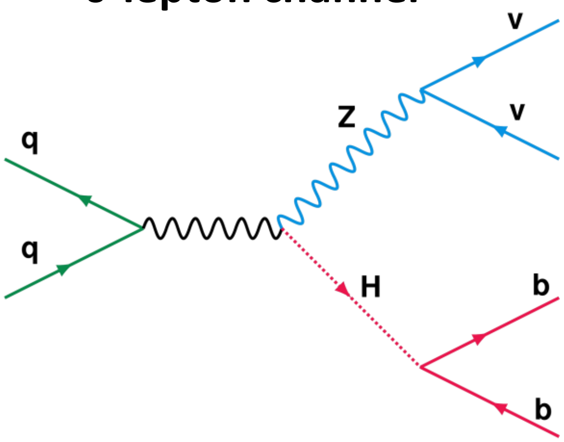
- Associated production with a vector boson V (V=Z or W)
  - V leptonic decay → clear signature

VH, H→b$\bar{b}$ channel

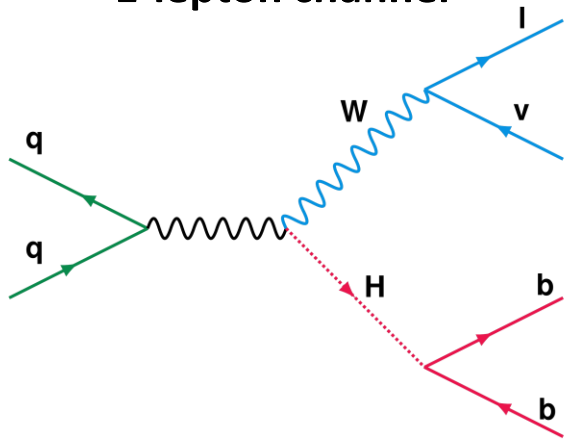
Three topologies studied:

- **H→b$\bar{b}$, Z→ ν$\bar{\nu}$** ⟶ 0 charged leptons
- **H→b$\bar{b}$, W→ lν** (l=e,μ) ⟶ 1 charged lepton
- **H→b$\bar{b}$, Z→ l$\bar{l}$** (l=e,μ) ⟶ 2 charged leptons

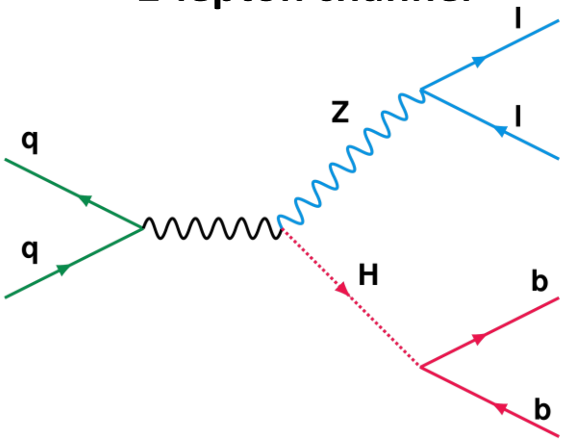
0-lepton channel



1-lepton channel



2-lepton channel



Trigger: E_T^{miss}

Trigger: electron (l=e) or E_T^{miss} (l=μ)

Trigger: lepton

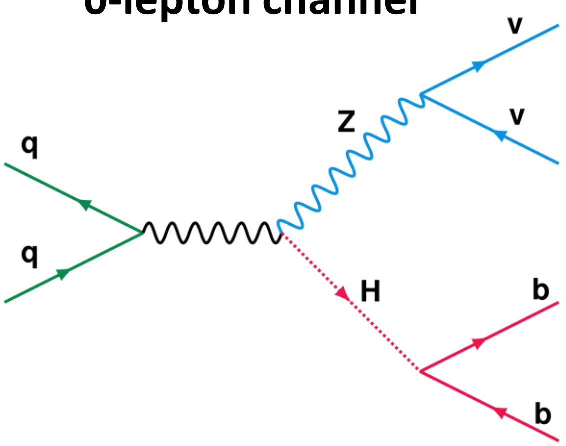
Event selection

Higgs decay production selection

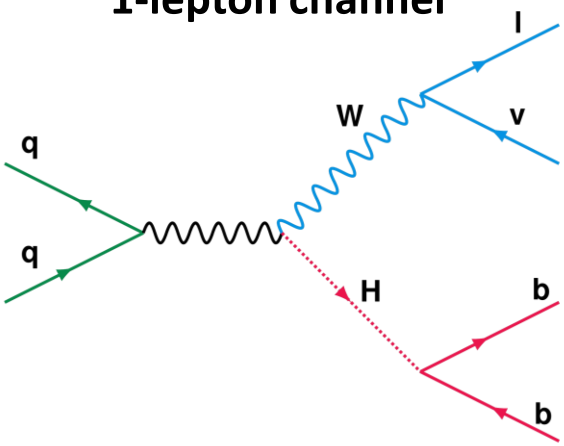
- **2 or 3 jets** (or more *)
- exactly **2 jet *b*-tagged** (MV2c10) with 70% b-jet eff.
  c-jet mis. eff: 12.5%, light jet mis. eff.: 0.3%

*only in 2-lepton channel

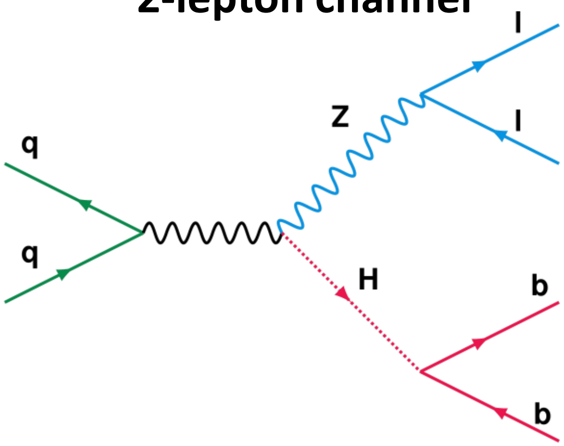
0-lepton channel



1-lepton channel



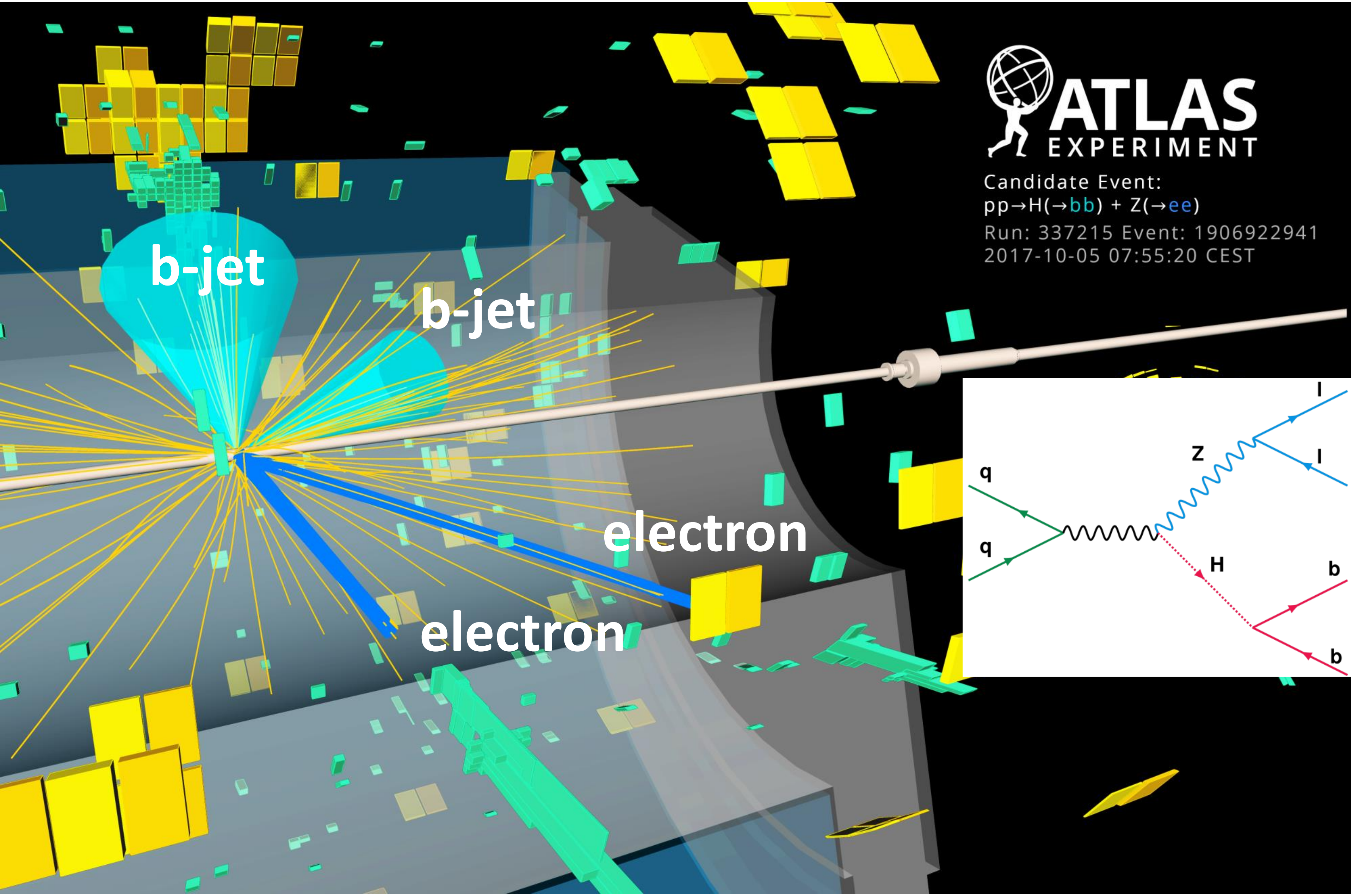
2-lepton channel



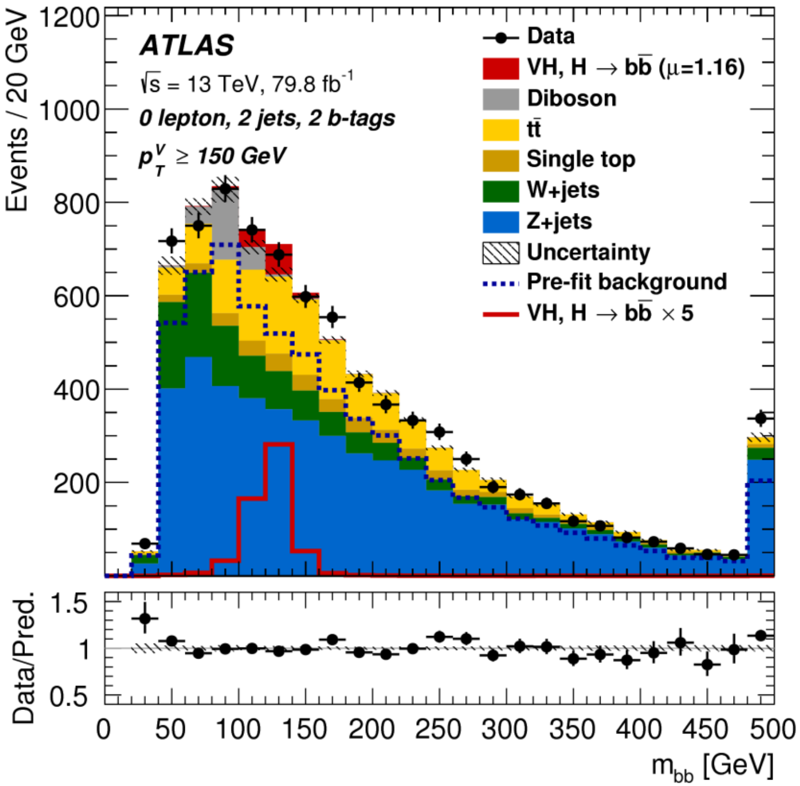
- 0 charged leptons
- $E_T^{miss} > 150$ GeV
- Angular cuts to reduce multi-jet background

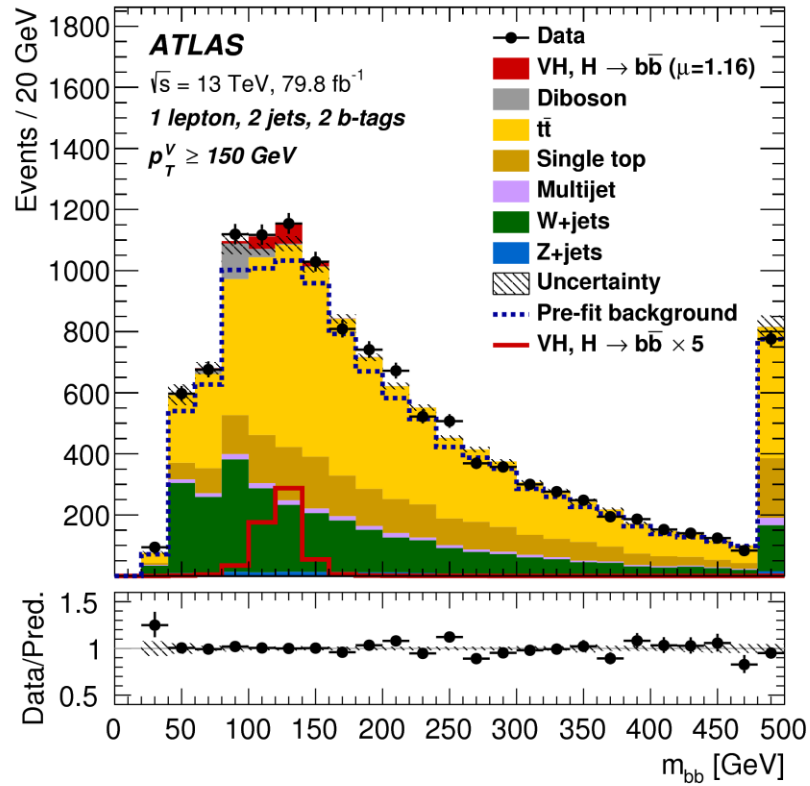
- 1 charged lepton
- $p_T^W > 150$ GeV

- 2 charged leptons
- Z mass:
  81 GeV < m_{ll} < 101 GeV
- 75 GeV < p_T^Z < 150 GeV, p_T^Z > 150 GeV


ATLAS
EXPERIMENT
Candidate Event:
pp→H(→bb) + Z(→ee)
Run: 337215 Event: 1906922941
2017-10-05 07:55:20 CEST
b-jet
b-jet
electron
electron
q
q
Z
H
l
l
b
b

Main backgrounds





- Main backgrounds modelled using simulated samples
- **Z+jets** and **W+jets**
- Top (**ttbar** and **single-top**)

  } Dominant backgrounds, studied with control regions
- Diboson (**WZ, ZZ**) → final state similar to VH, used to validate the analysis
- **Multi-jet** → suppressed with dedicaded cuts, contribution studied using a data-driven method

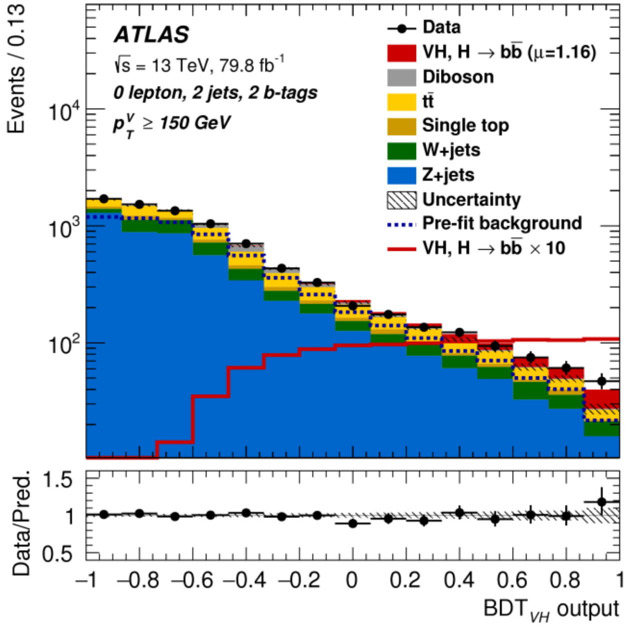
arXiv:1808.08238

Multivariate analysis

Variable	0-lepton	1-lepton	2-lepton
→ p_T^V	$\equiv E_T^{miss}$	×	×
→ E_T^{miss}	×	×	
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
→ m_{bb}	×	×	×
→ $\Delta R(\vec{b_1}, \vec{b_2})$	×	×	×
$\|\Delta\eta(\vec{b_1}, \vec{b_2})\|$	×		
$\Delta\phi(\vec{V}, \vec{bb})$	×	×	×
$\|\Delta\eta(\vec{V}, \vec{bb})\|$			×
m_{eff}	×		
$\min[\Delta\phi(\vec{\ell}, \vec{b})]$		×	
m_T^W		×	
$m_{\ell\ell}$			×
$E_T^{miss}/\sqrt{S_T}$			×
m_{top}		×	
$\|\Delta Y(\vec{V}, \vec{bb})\|$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

Boosted Decision Tree (BDT)

- Input: **kinematics variables**
- Output: BDT variable
  → discriminate between signal and bkg events



Profile Likehood Fit to the BDT distributions
→ to extract the *signal strength μ*

$$\mu_{VH} \cdot \mu_{H\to b\bar{b}} = \frac{(\sigma(VH) \times BR(H \to b\bar{b}))_{measured}}{(\sigma(VH) \times BR(H \to b\bar{b}))_{expected}(SM)}$$

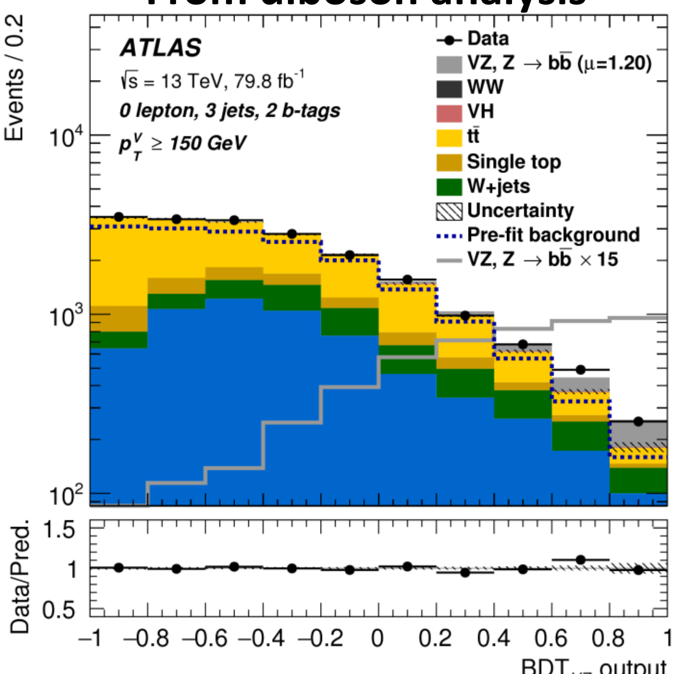
arXiv:1808.08238

Results of VH, H→$b\bar{b}$ analysis

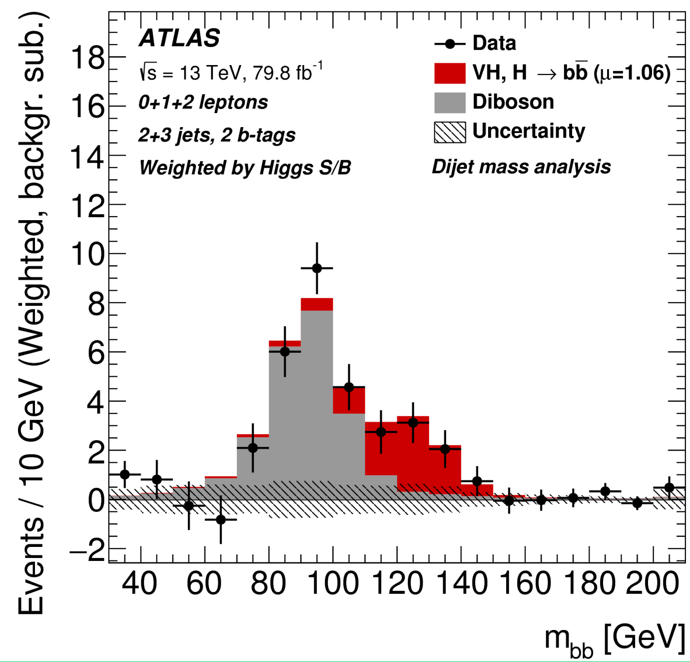
Signal strength	Signal strength	p_0		Significance	
		Exp.	Obs.	Exp.	Obs.
0-lepton	$1.04^{+0.34}_{-0.32}$	$9.5 \cdot 10^{-4}$	$5.1 \cdot 10^{-4}$	3.1	3.3
1-lepton	$1.09^{+0.46}_{-0.42}$	$8.7 \cdot 10^{-3}$	$4.9 \cdot 10^{-3}$	2.4	2.6
2-lepton	$1.38^{+0.46}_{-0.42}$	$4.0 \cdot 10^{-3}$	$3.3 \cdot 10^{-4}$	2.6	3.4
$VH,\ H \to b\bar{b}$ combination	$1.16^{+0.27}_{-0.25}$	$7.3 \cdot 10^{-6}$	$5.3 \cdot 10^{-7}$	4.3	4.9

Cut-based selection and **diboson analysis** used to validate the multivariate analysis

From diboson analysis



From cut-based analysis



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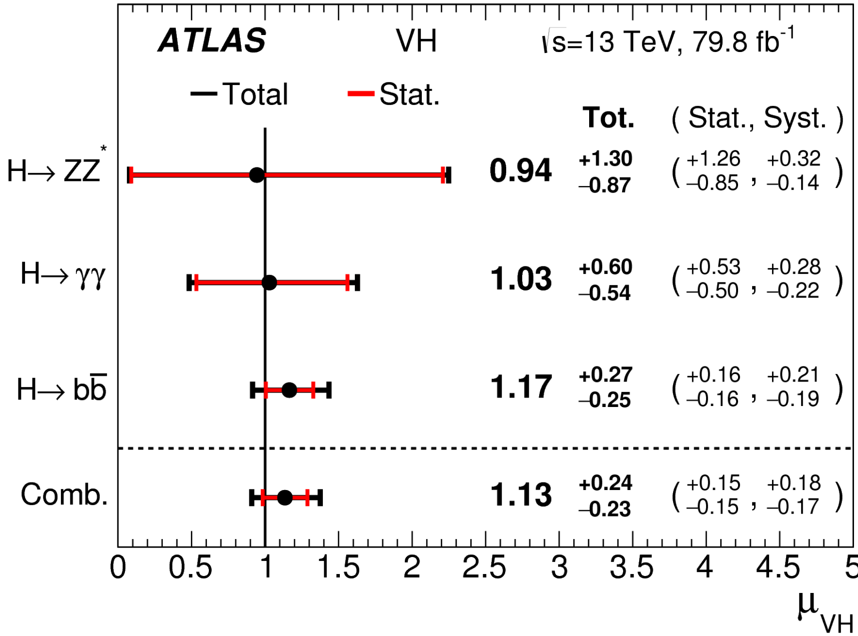
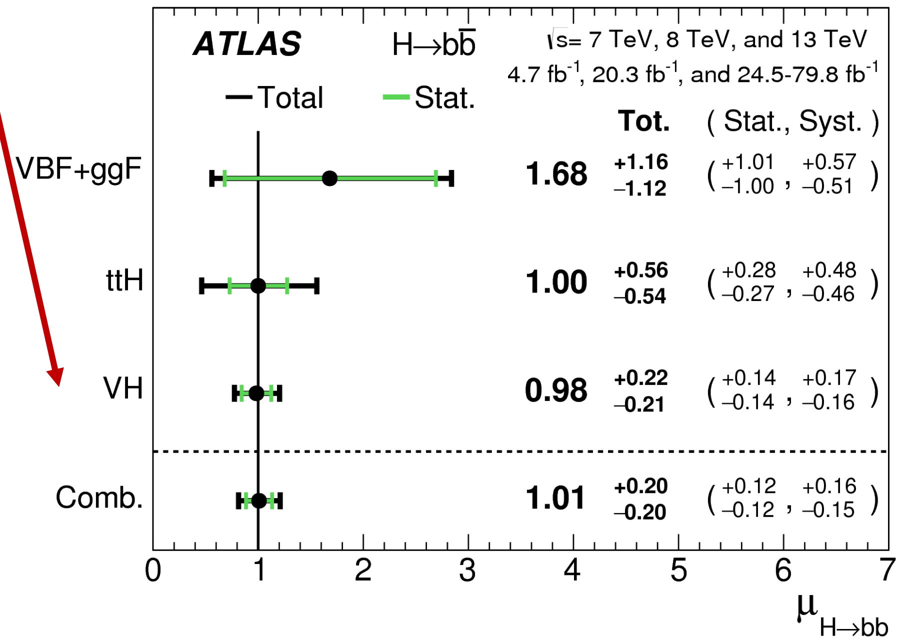
Observation of VH and $H\to b\bar{b}$

Leading sensitivity from VH, $H\to b\bar{b}$ analysis





Combination with other decay modes
Observed significance: **5.3 σ**

First **observation** of **VH** production mode

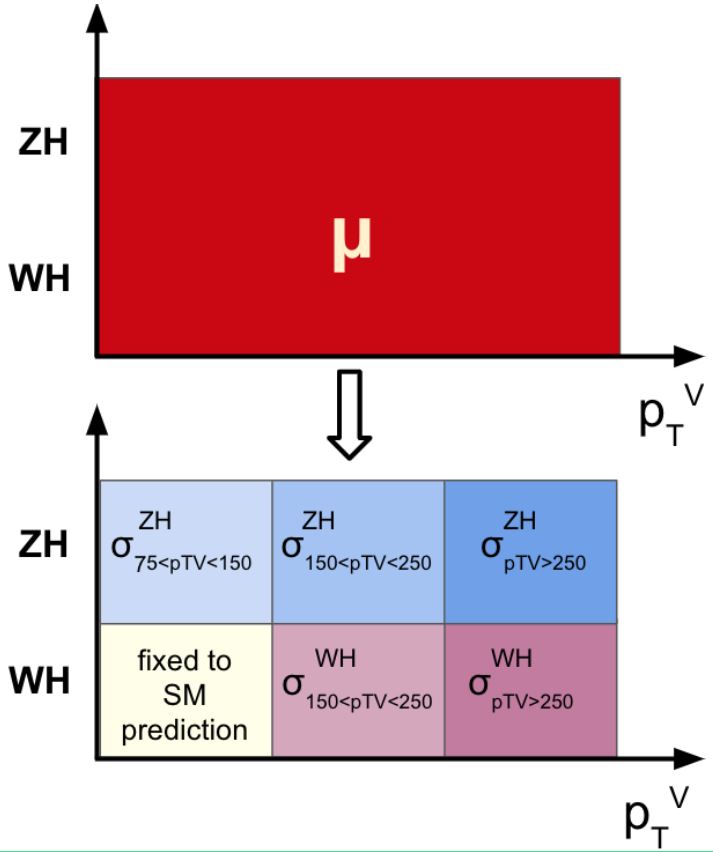
Combination with other production modes
Observed significance: **5.4 σ**

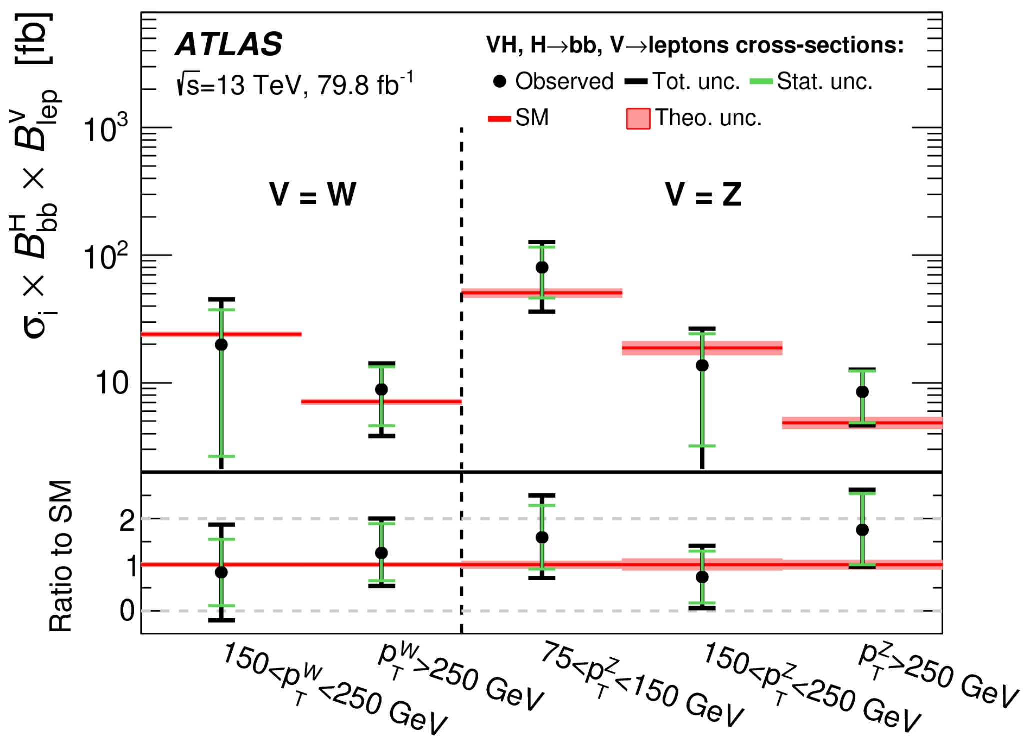
First **observation** of **$H\to b\bar{b}$** decay mode

Simplified template cross-sections

- Same event classification and selection
- Signal parametrization (done at truth level):
  - Production mode → ZH or WH
  - p_T^V → cut at 75 GeV, 150 GeV and 250 GeV

Differential pp → VH cross section measurements





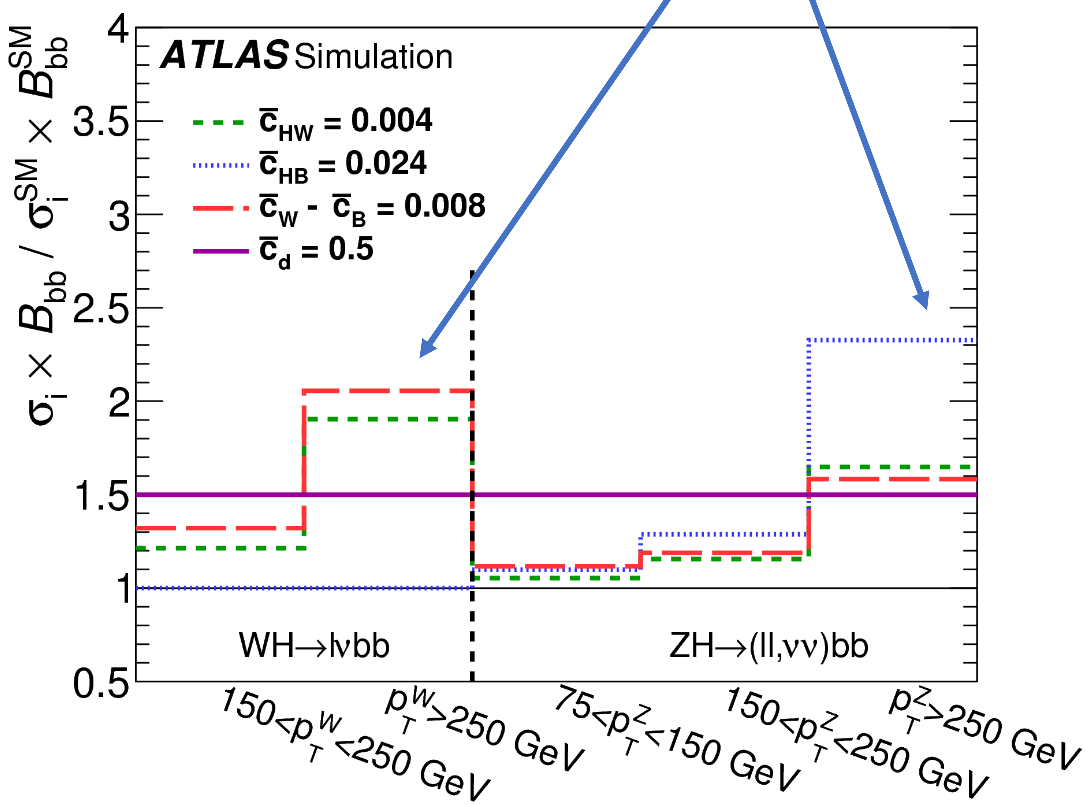
Constraints on BSM effects

Parameterization of BSM effects using **effective Lagrangian** with **dimension-6 operators** in the SILH* basis

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i c_i^{(6)} O_i^{(6)} / \Lambda^2$$

- $c_i^{(6)}$ = Wilson coefficient
- $O_i^{(6)}$ = dimension-6 operator
- Λ = BSM energy scale

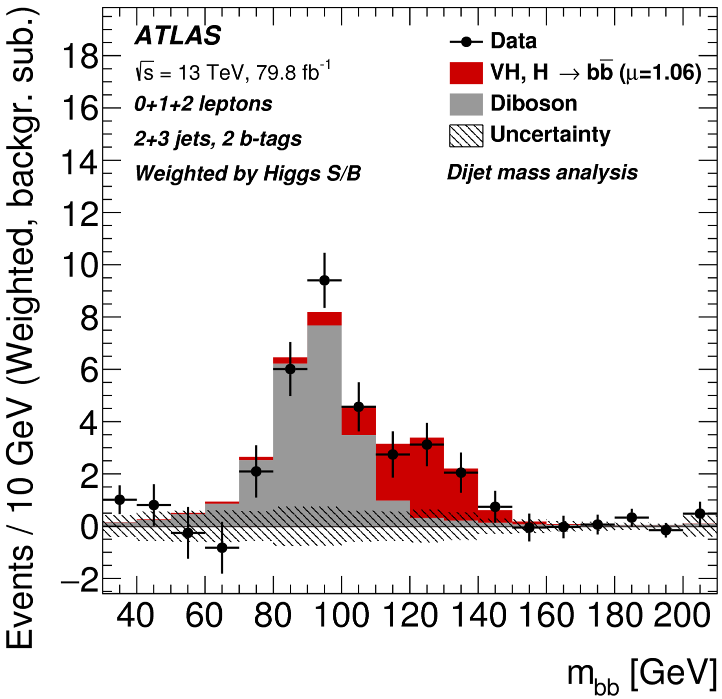
Events at high energy more sensitive to Beyond the Standard Model effects (**BSM**)



*SILH= Strongly Interacting Light Higgs

Conclusions

- First **observation** of **H→b$\bar{b}$** decay mode
- First **observation** of **VH** production mode
- First **differential cross section pp → VH measurement**
- Studies of **BSM effects:**
  - **constraints** on Wilson coefficients
  - possible **BSM deviations** are more **evident at high momentum**



BACKUP SLIDES

Detailed event selection

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 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

- **Lepton selection**
- **Higgs selection**
- **Multi-jet cuts**

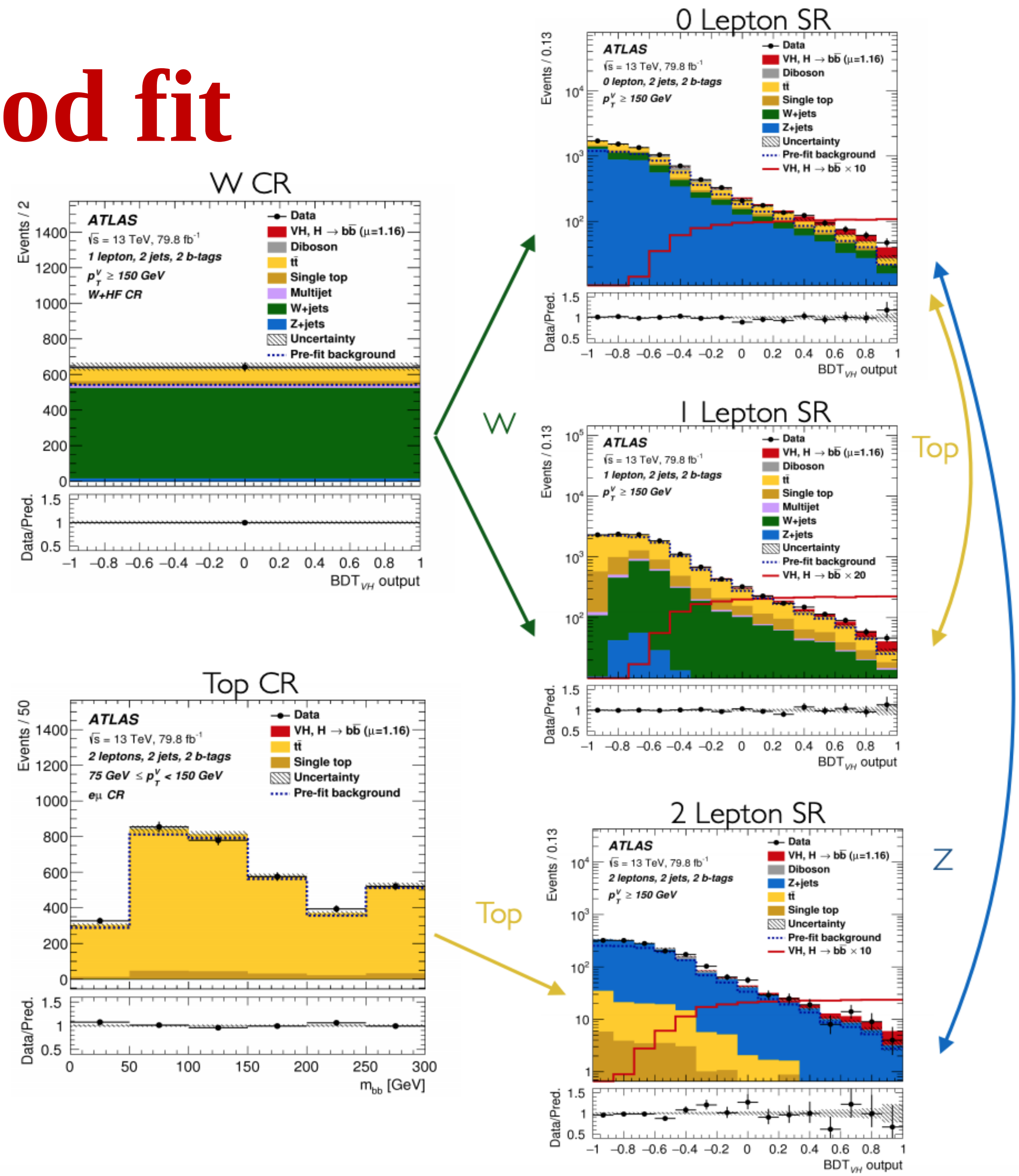
Detailed event categorization

	0-Lepton	1-Lepton	2-Leptons	
	$p_T^V > 150$ GeV	$p_T^V > 150$ GeV	$75 < p_T^V < 150$ GeV	$p_T^V > 150$ GeV
2 jet	SR	SR	SR	SR
3(+) jet	SR	SR	SR	SR
2 jet		W CR	Top CR	Top CR
3(+) jet		W CR	Top CR	Top CR

Profile likelihood fit

- Simultaneous **fit** on the **14 regions (8 SR + 6 CR)**

- **Top CR**
- **W+HF CR**
- In 0-lepton channel
  - **Z** estimated with 2-lepton
  - **Top** estimated with 1-lepton



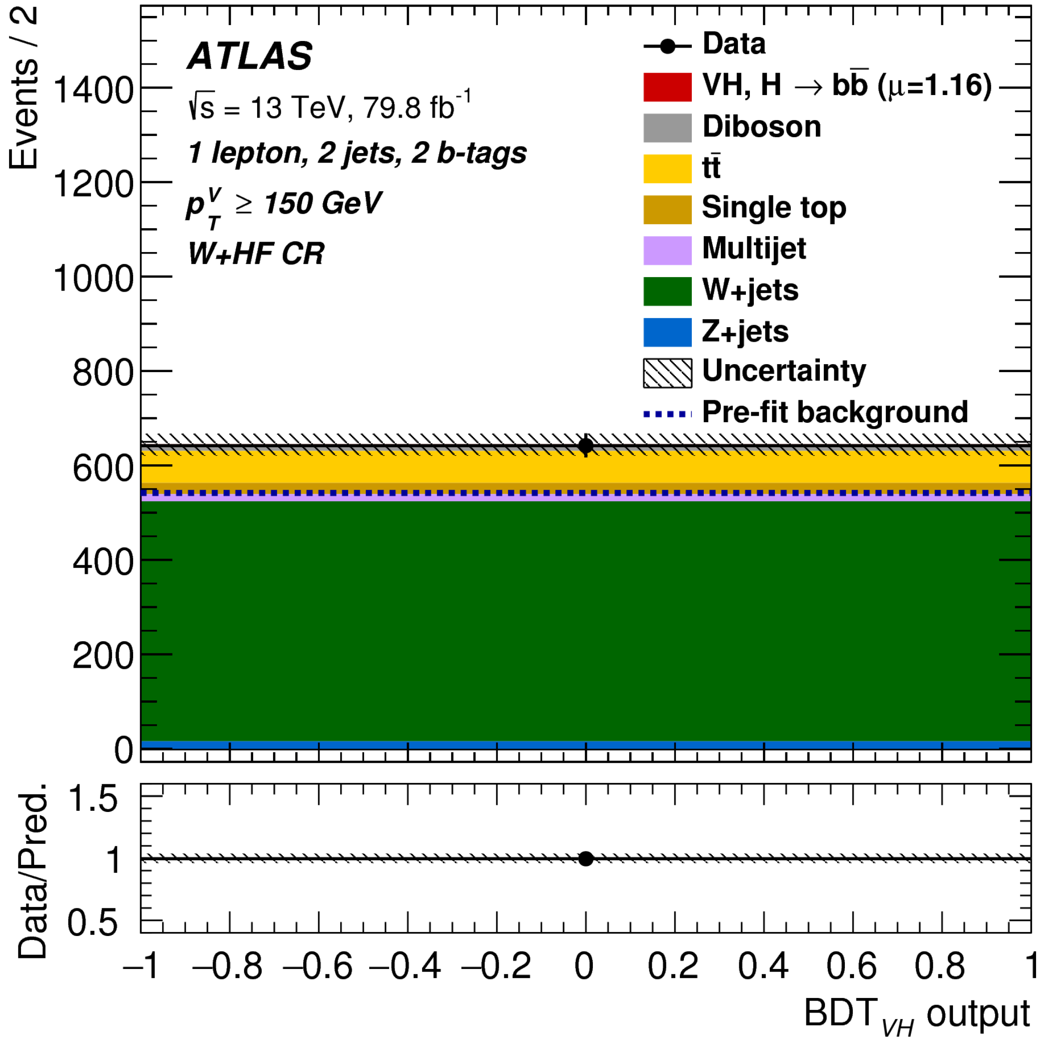
W+HF control region

- CRs are orthogonal to the signal regions, with negligible level of signal contamination
- **W+HF CR** built in **1-lepton** channel splitting events in **2 jets** and **3 jets**.
- **~75% purity**

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

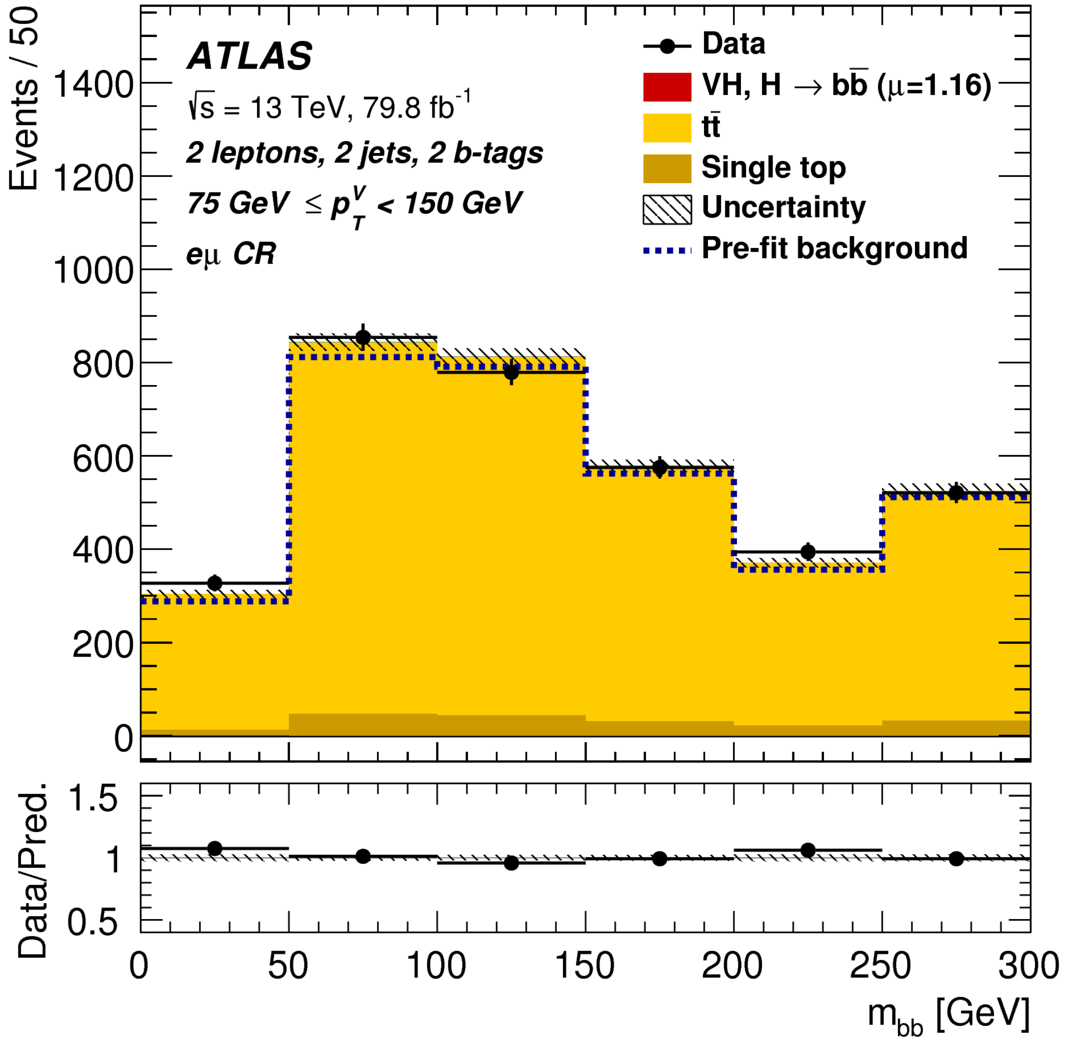
Reduce VH contamination

Reduce top contamination



$e\mu$ control region

- CRs are orthogonal to the signal regions, with negligible level of signal contamination
- ***eμ* CR** built in **2-lepton** channel splitting events in **2 jets** and **3+ jets**.
- Very pure CR to constraint top events



Systematics uncertainties

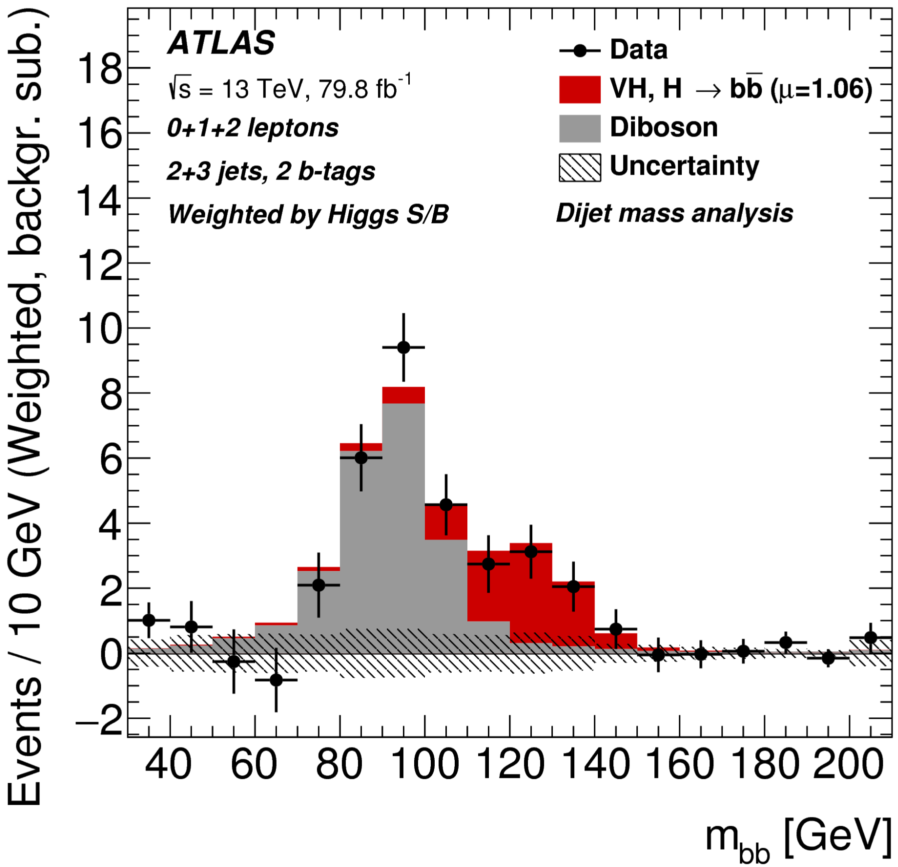
- Analysis **limited** by **systematics uncertainties**
- Main systematics:
  - **Flavor tagging calibration**
  - **Signal and background modelling**
  - **MC stat**

Source of uncertainty		σ_μ
Total		0.259
Statistical		0.161
Systematic		0.203
Experimental uncertainties		
Jets		0.035
E_T^{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

Results of cut-based analysis

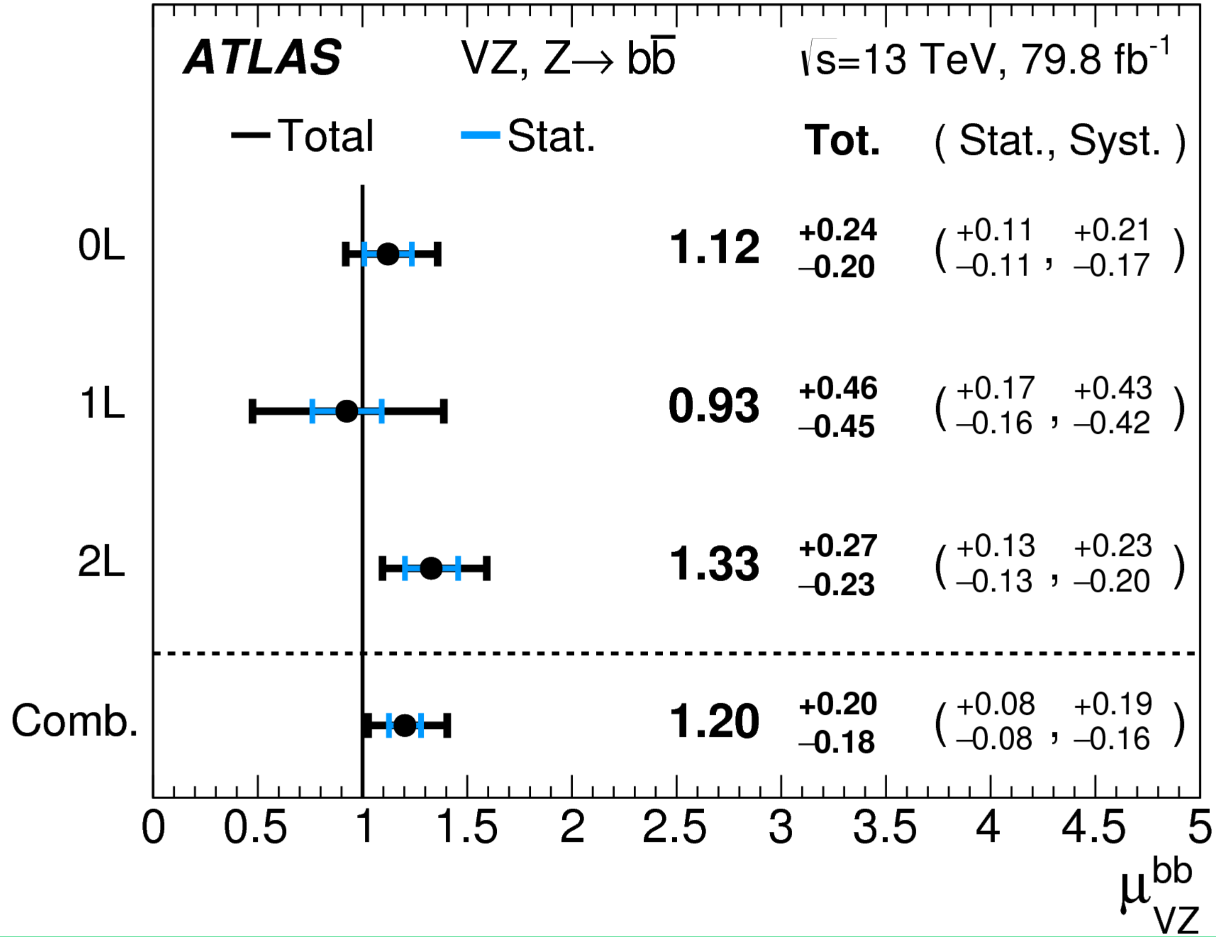
$$\mu_{VH}^{bb} = 1.06^{+0.36}_{-0.33} = 1.06 \pm 0.20(\text{stat.})^{+0.30}_{-0.26}(\text{syst.}),$$

Observed significance: **3.6 σ**



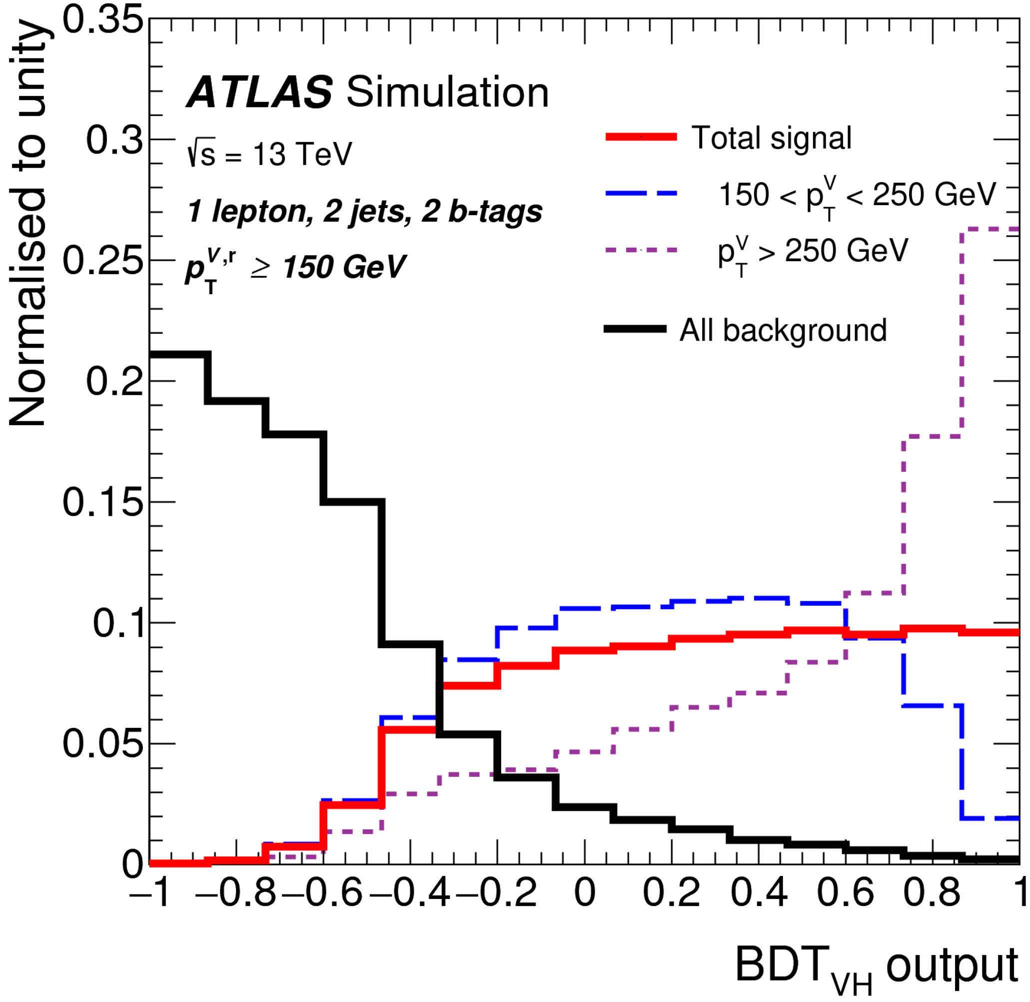
Results of diboson analysis

$$\mu_{VZ}^{bb} = 1.20^{+0.20}_{-0.18} = 1.20 \pm 0.08(\text{stat.})^{+0.19}_{-0.16}(\text{syst.}),$$

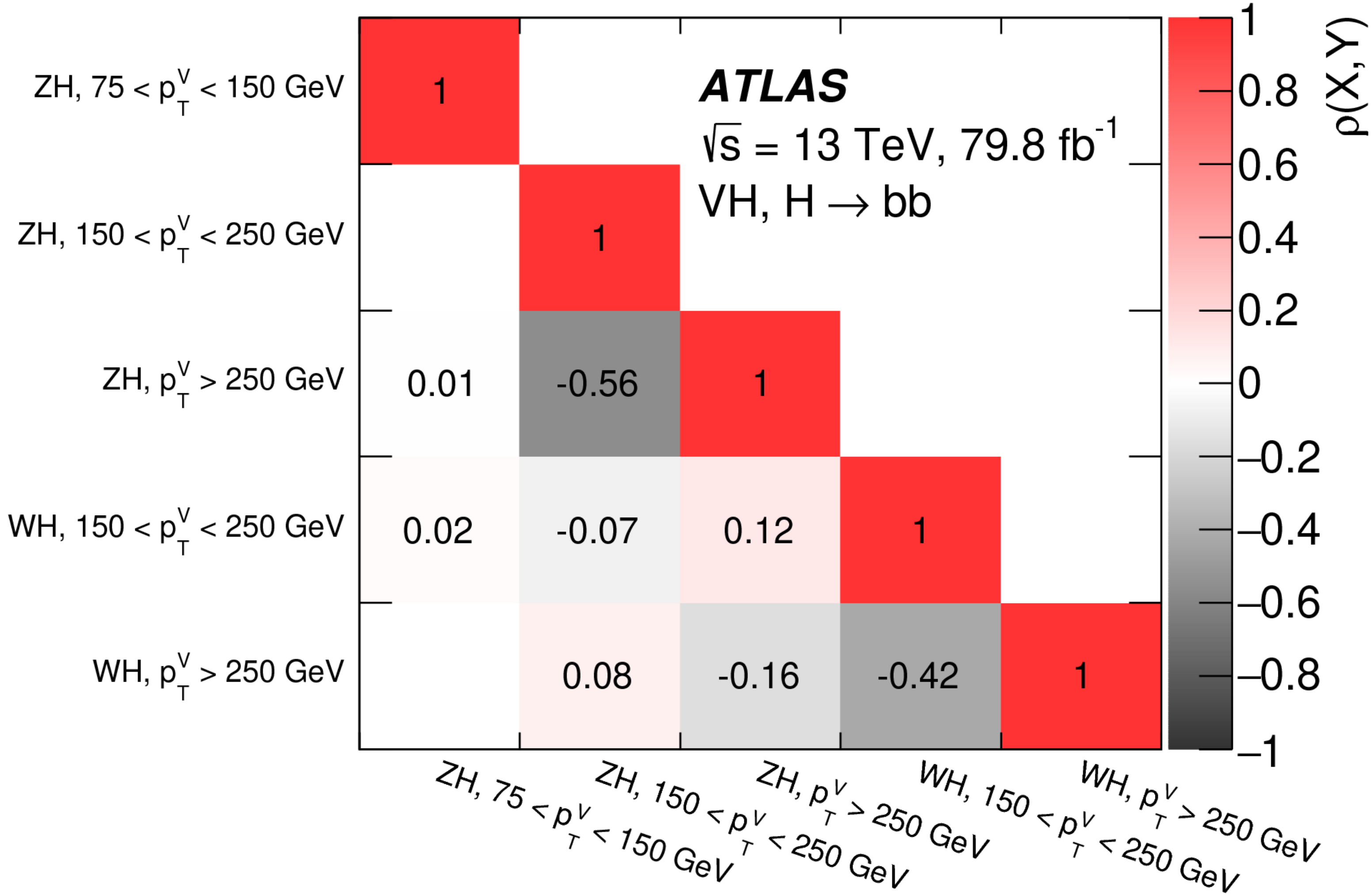


BDT distribution 1L

- Different BDT shape between signal events according to pTV value



Correlation matrix STXS fit



Relating STXS to EFT

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

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

Linear term

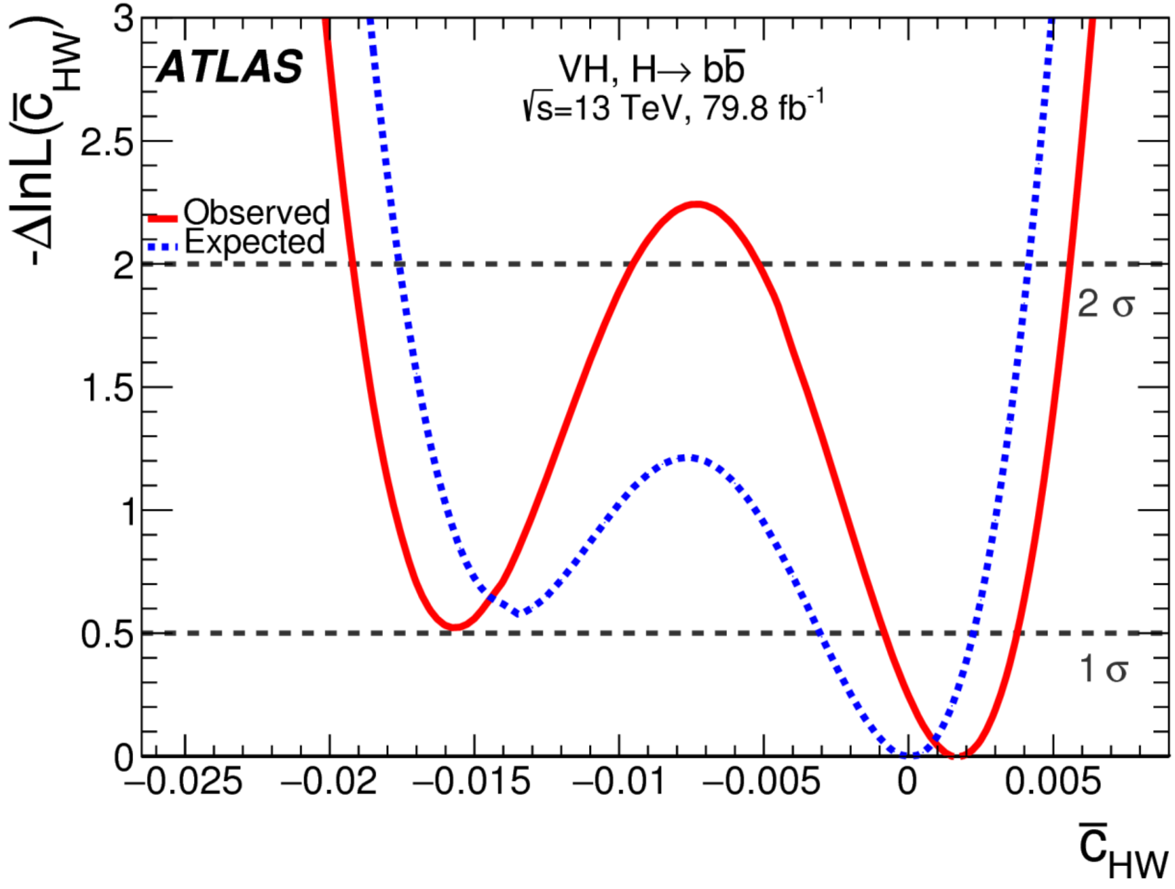
Quadratic term

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

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

Example of EFT constraint

1-D fits of the coefficients have been performed



EFT coefficients

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] ⋃ [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] ⋃ [−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] ⋃ [−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] ⋃ [−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])