Observation of H→bb decays in the VH production mode and first differential measurement with the ATLAS detector

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University of Toronto

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Outline

- Observation of H→bb decays with the ATLAS detector (L=79.8 fb^{-1})

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- Measurement of the VH→bb production as a function of the vector-boson transfer momentum with the ATLAS detector (L=79.8 fb^{-1})

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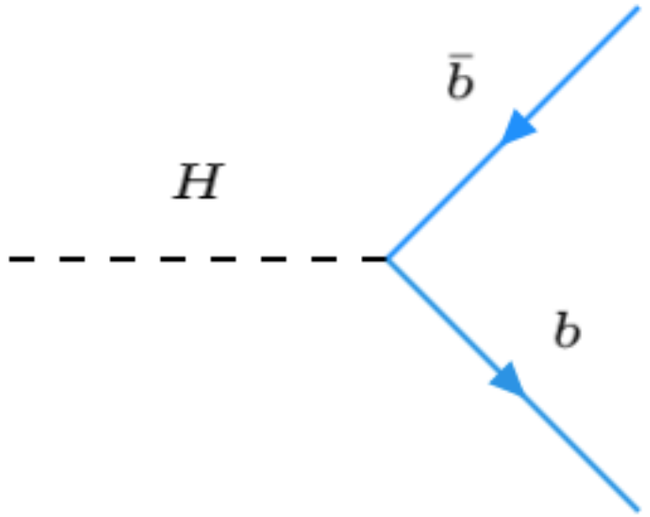
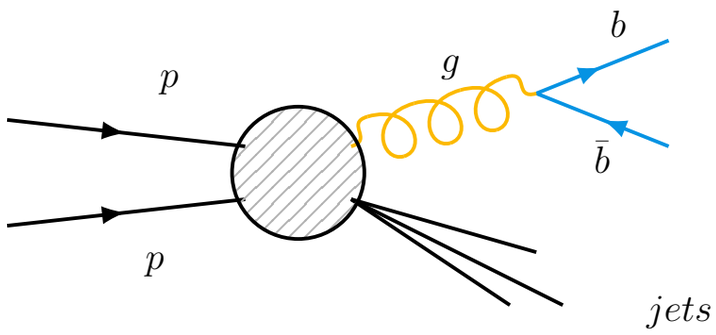
Observation of H→bb decays with the ATLAS detector

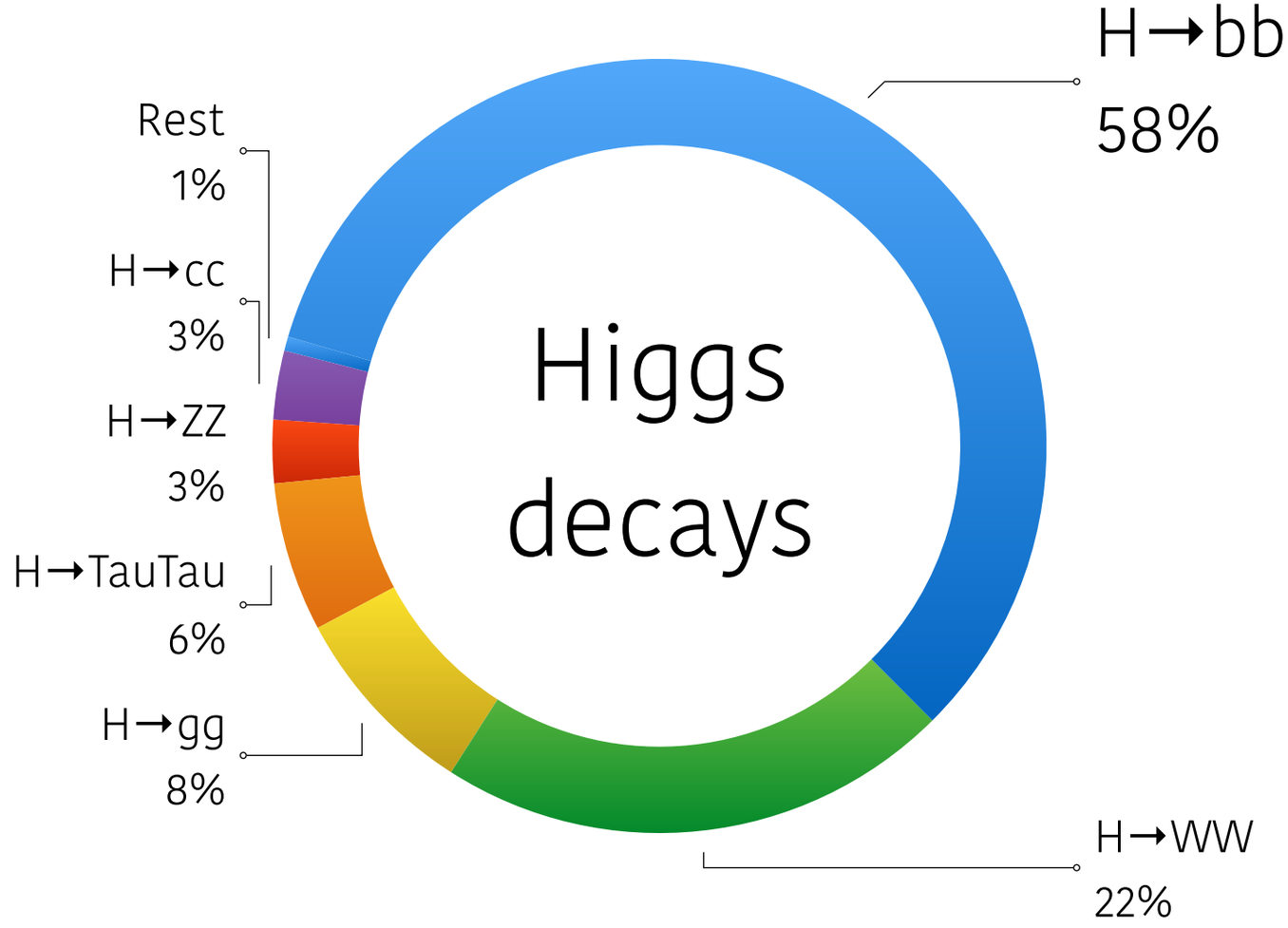
H→bb

- ***Motivations***:
  - *largest Branching Ratio;*
  - *driving uncertainty for the total Higgs boson width;*
  - *measurement of the Yukawa Coupling to down type quarks.*



- ***Main challenge***:
  - *large QCD background.*

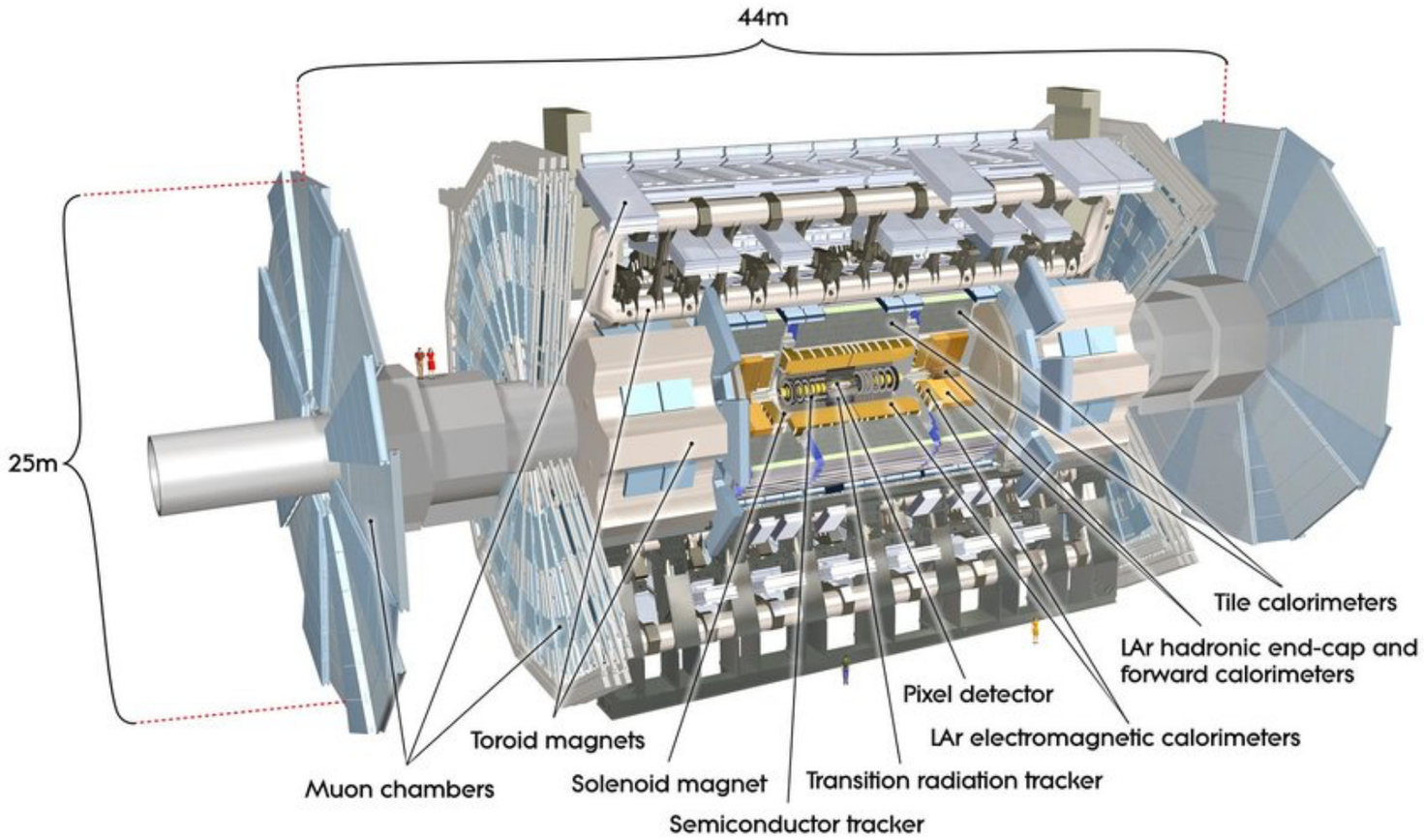


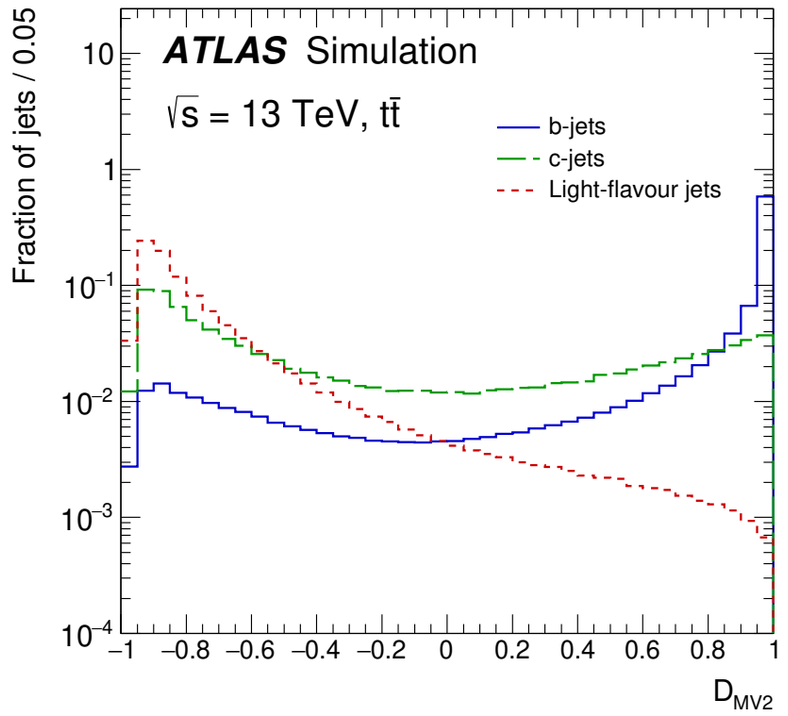


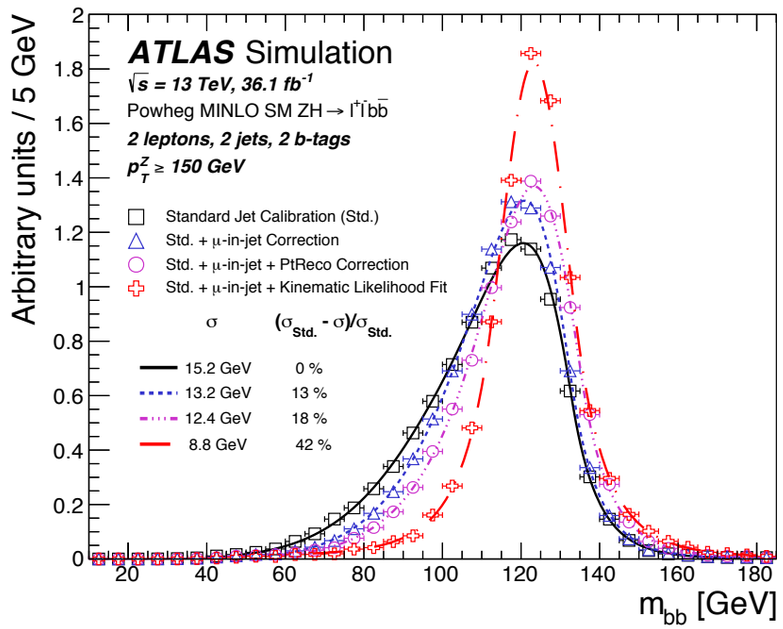
ATLAS detector

Few key ingredients for searching for H→bb:

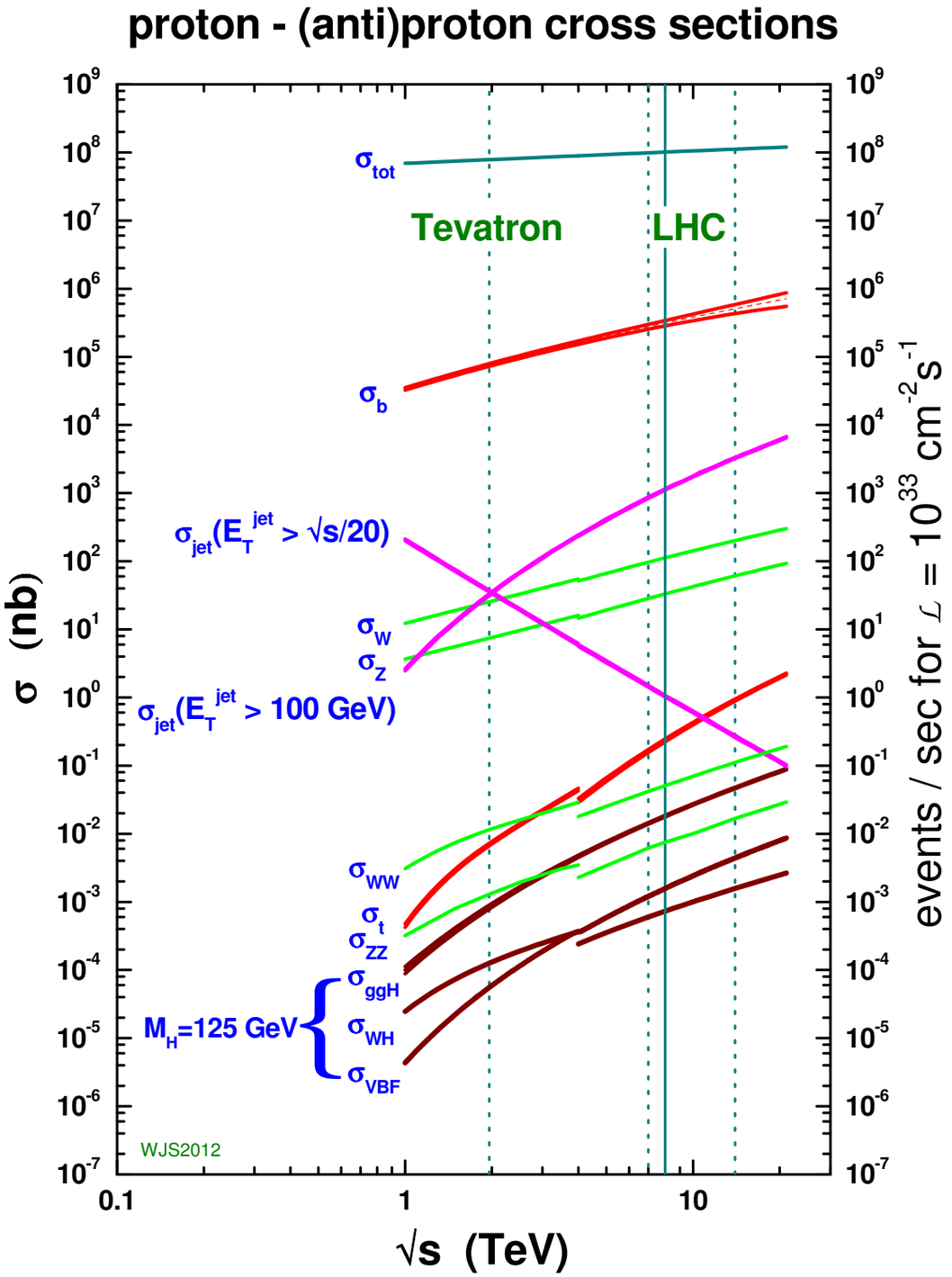
- high **b-tagging efficiency** from the tracker;
- good **energy resolution** from the calorimeters.







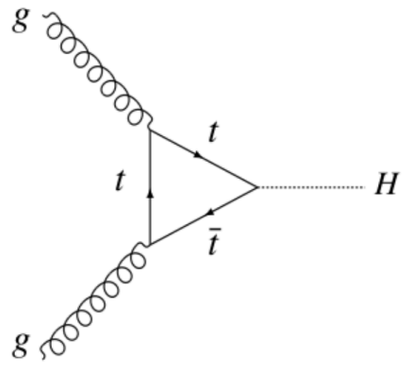
Higgs production at the LHC (@13TeV)



Source: W.J. Stirling

Gluon fusion

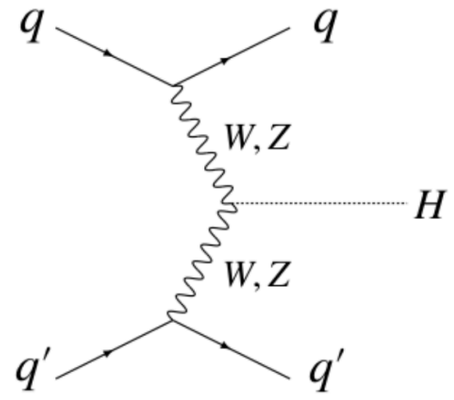
(σ_{ggF} = 43.9 pb)



Only for the boosted regime.

Vector boson fusion

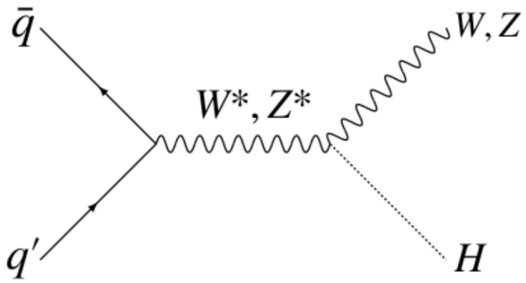
(σ_{VBF} = 3.75 pb)



Searched with an associated γ.

Associate production with a vector boson

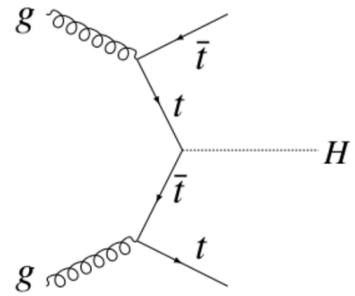
(σ_{WH} = 1.38 pb, σ_{ZH} = 0.870 pb)



Most sensitive production H→bb.

Associate production with a top pair

(σ_{ZH} = 0.509 pb)

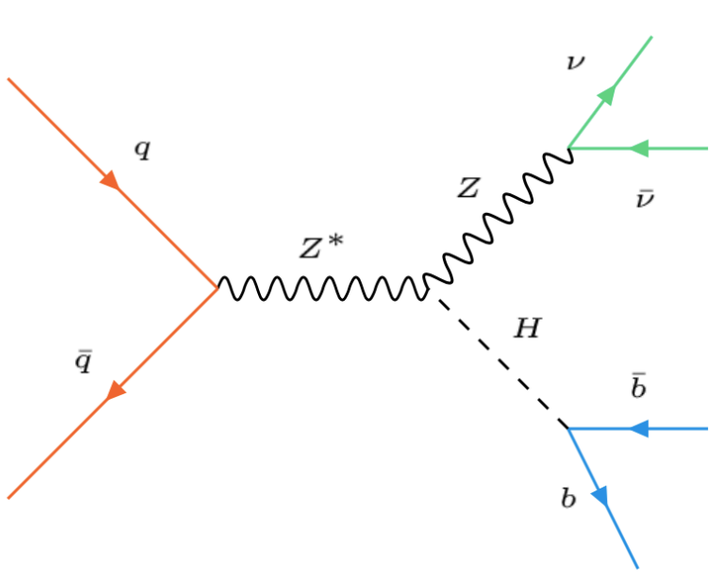


Small cross-section.

Search for VH→bb

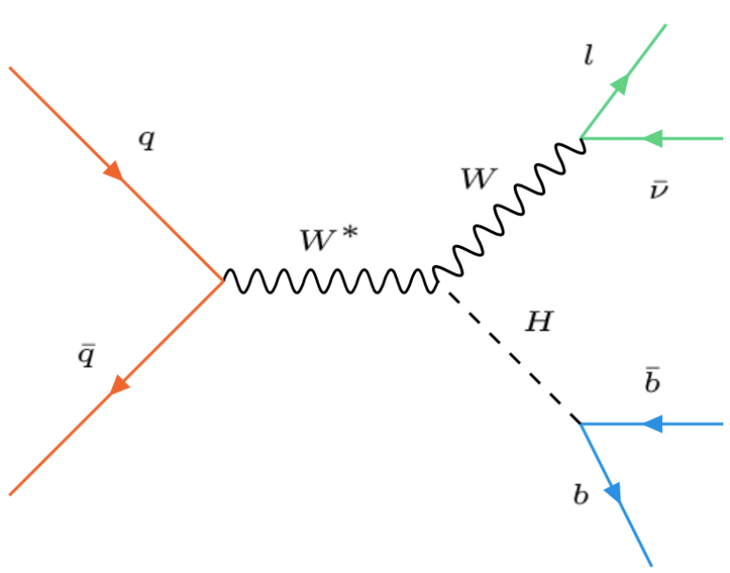
- *2 b-jets per event.*
- *0 or 1+ more additional jets.*
- *3 decay channels according to the number of charged leptons (0, 1, 2).*

0-Lepton



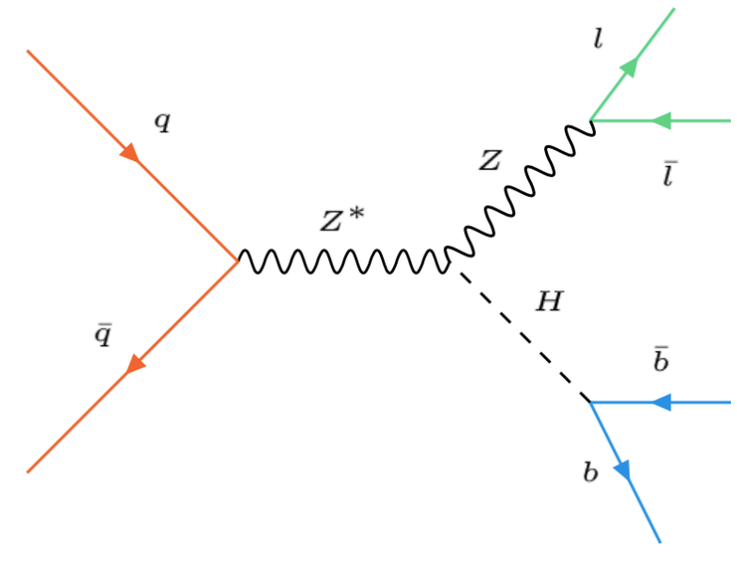
- Target: mainly Z→νν but also W→lν
- E_T^{miss} trigger
- Lepton veto
- Reconstructed E_T^{miss} > 150 GeV

1-Lepton



- Target: mainly W→lν
- Lepton or E_T^{miss} trigger
- p_T^{Lep}> 25 (27) GeV for μ (e)
- p_T^{W}> 150 GeV

2-Lepton



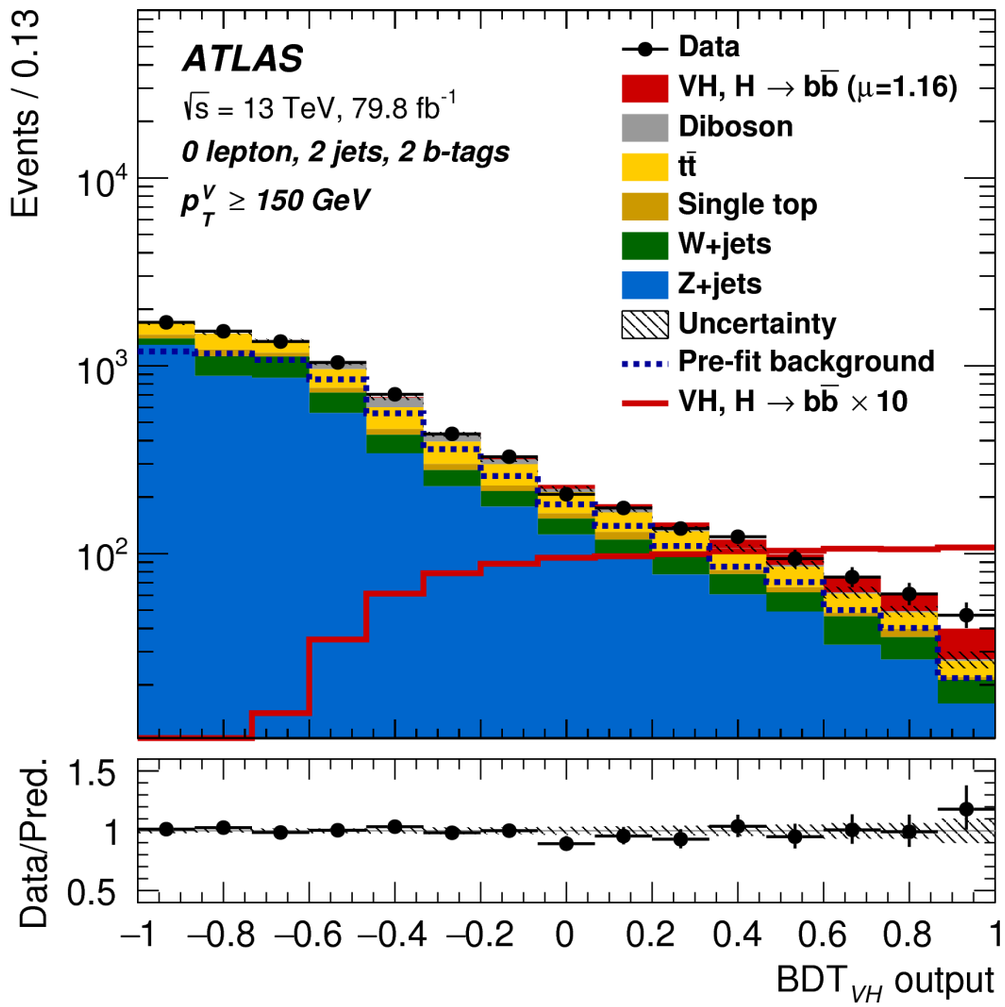
- Target: mainly Z→ll
- Single lepton triggers
- 2 lep same flav, opp charge in μμ ch
- p_T^{Z}> 75 GeV

Multivariate analysis

Several discriminating variables (m_{bb}, dR_{bb}, p_T^V..) to discriminate between signal and background:

1. construct BDTs to improve sensitivity;
2. perform separate trainings for each signal region;
3. use a binned maximum likelihood fit to extract the signal strength (μ).

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

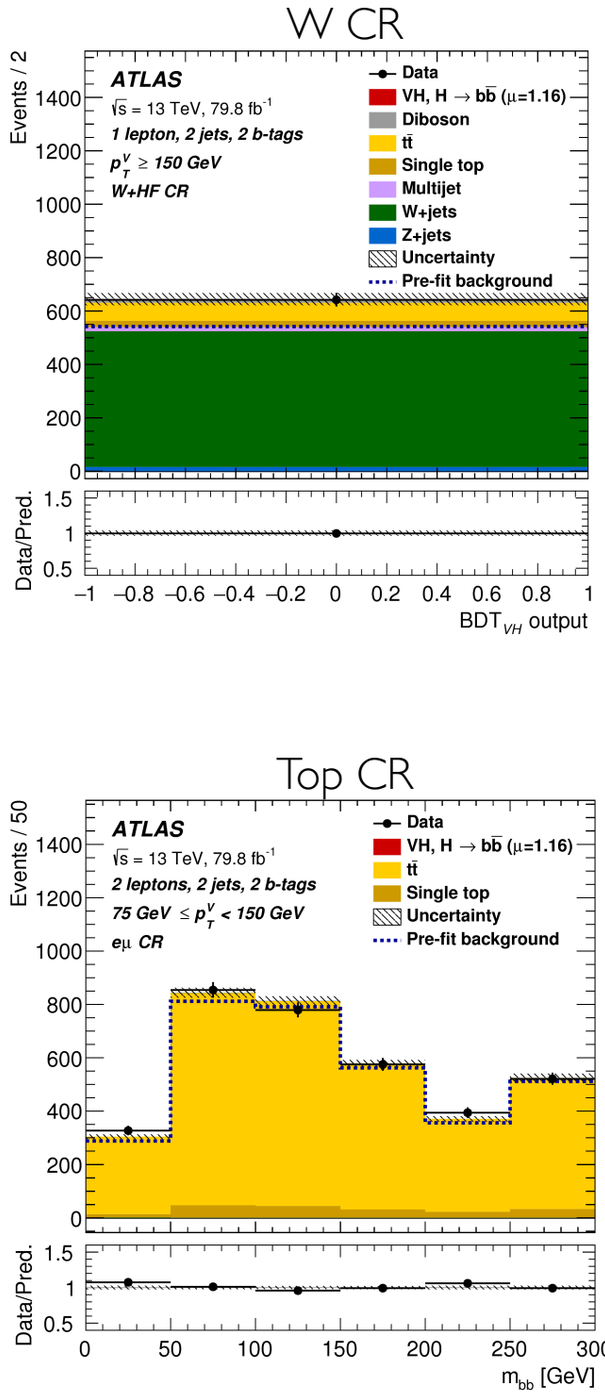


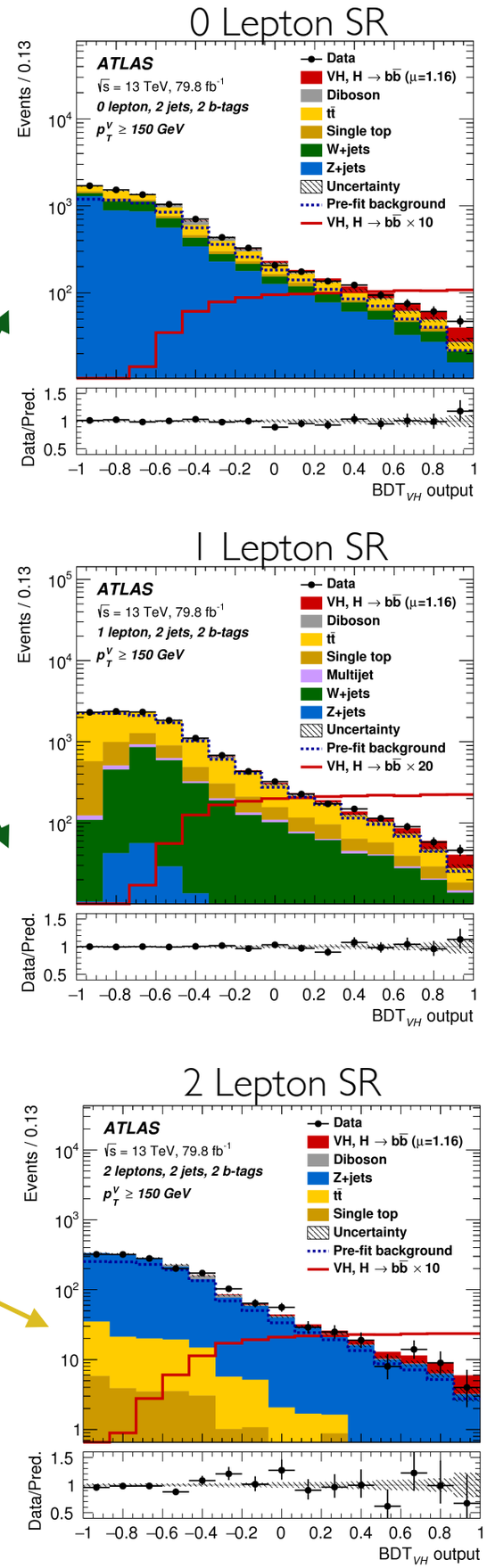
Profile likelihood fit

- Simultaneous fit of 14 analysis regions:

	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

- Top CR **eμ** events.
- W CR ($m_{bb} < 75$ GeV, $m_{Top} < 225$ GeV).
- In 0-Lep channel:
  - Z estimated with 2-Lep channel;
  - Top estimated with 1-Lep channel.





VH→bb results

- Measured signal strength (μ) for VH→bb with 79.8 fb^{-1} of data:

$$\mu_{VH}^{b\bar{b}} = \frac{\sigma_{obs}}{\sigma_{SM}} = 1.16^{+0.27}_{-0.25}$$

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- Observed significance 4.9σ (expected 4.3σ).

- Contributions for the individual lepton channels:

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

Systematic uncertainties

Analysis limited by

systematic uncertainties

Flavour-tagging calibrations

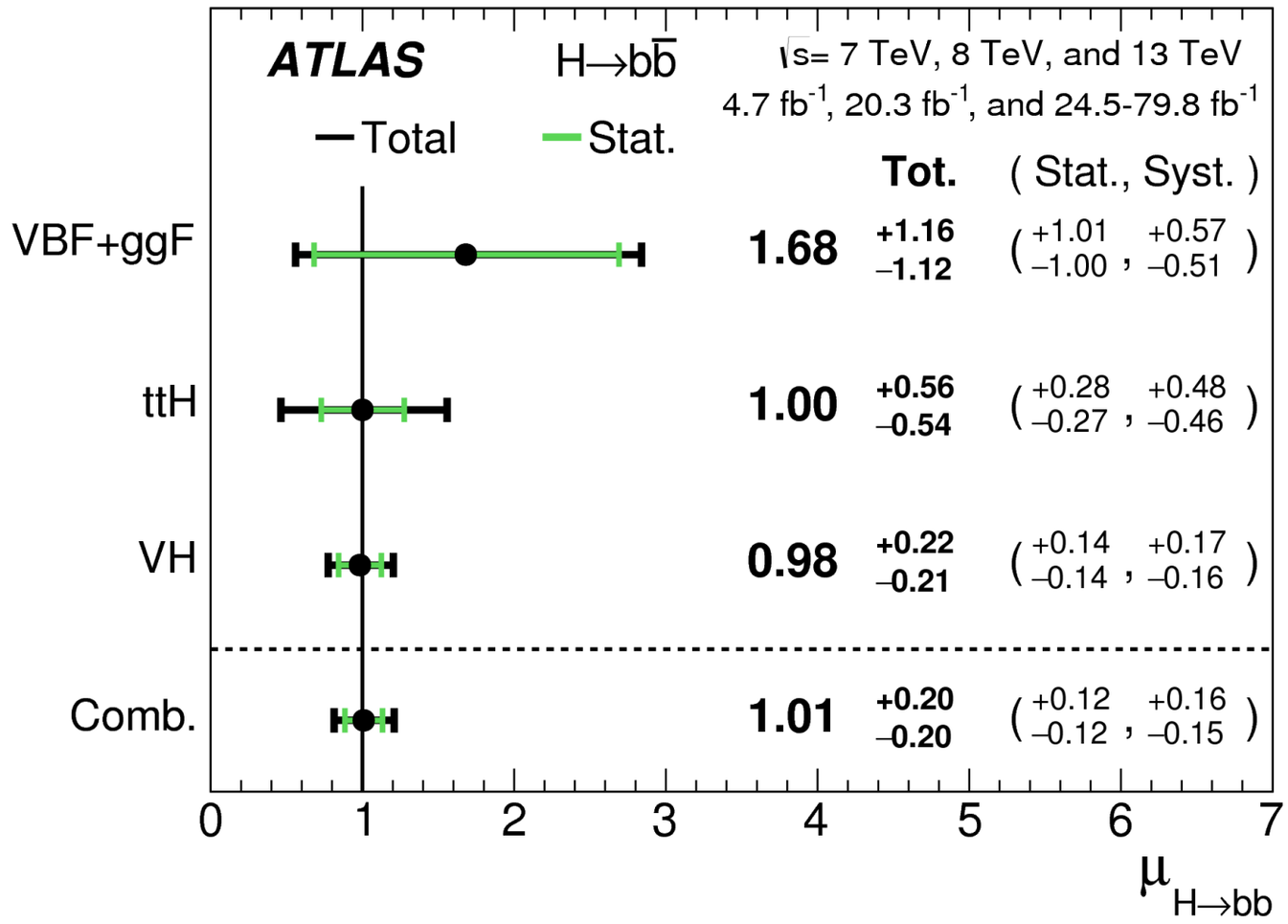
Signal and Background modelling

Limited MC statistics

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

H→bb combination

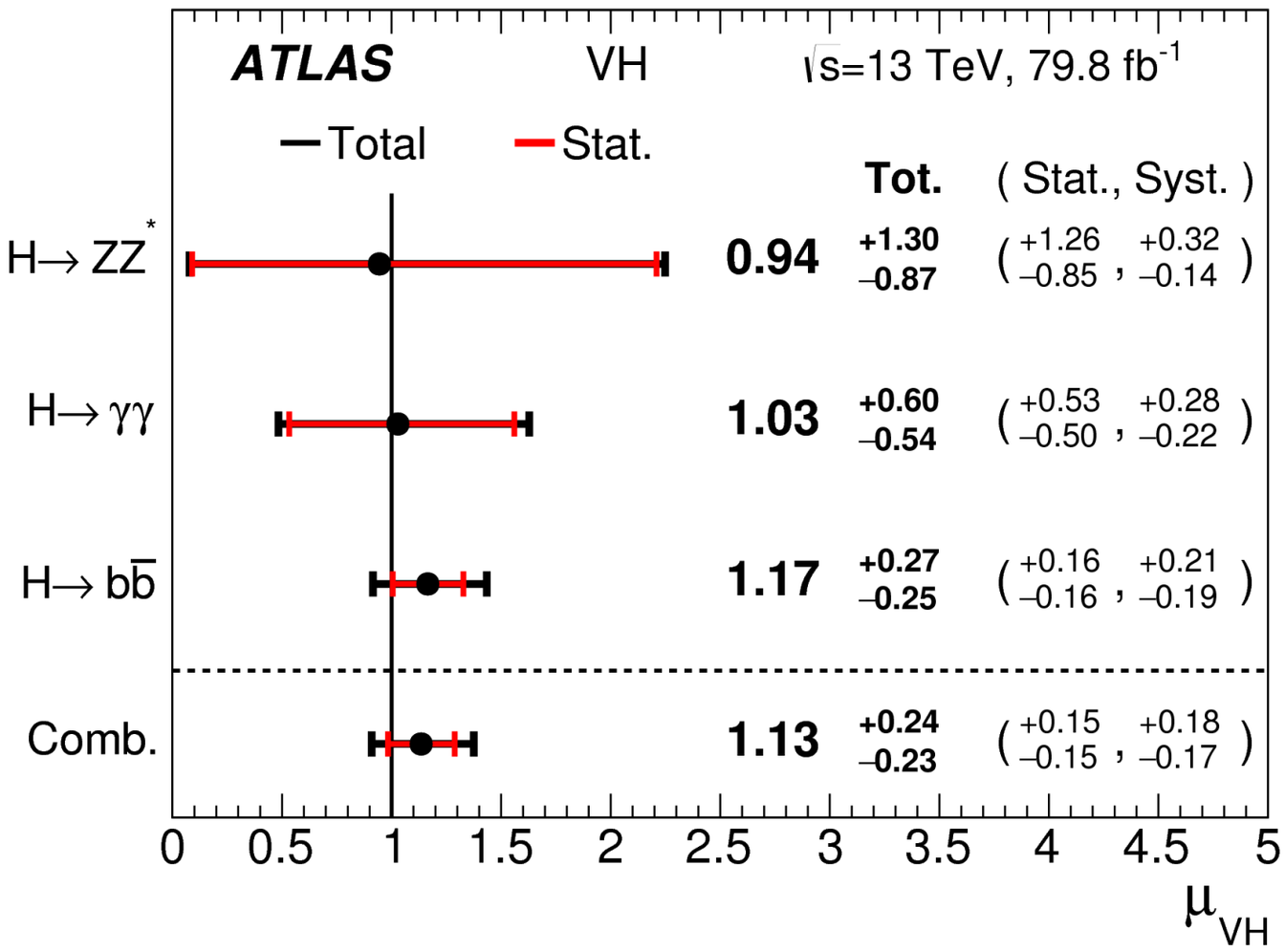
- The VH, VBF+ggF and ttH analysis of Run-1 and Run-2 have been combined:



- The result is the **observation** of H→bb decays at 5.4σ (5.5σ expected).

VH production

- The Run-2 VH results have been combined:



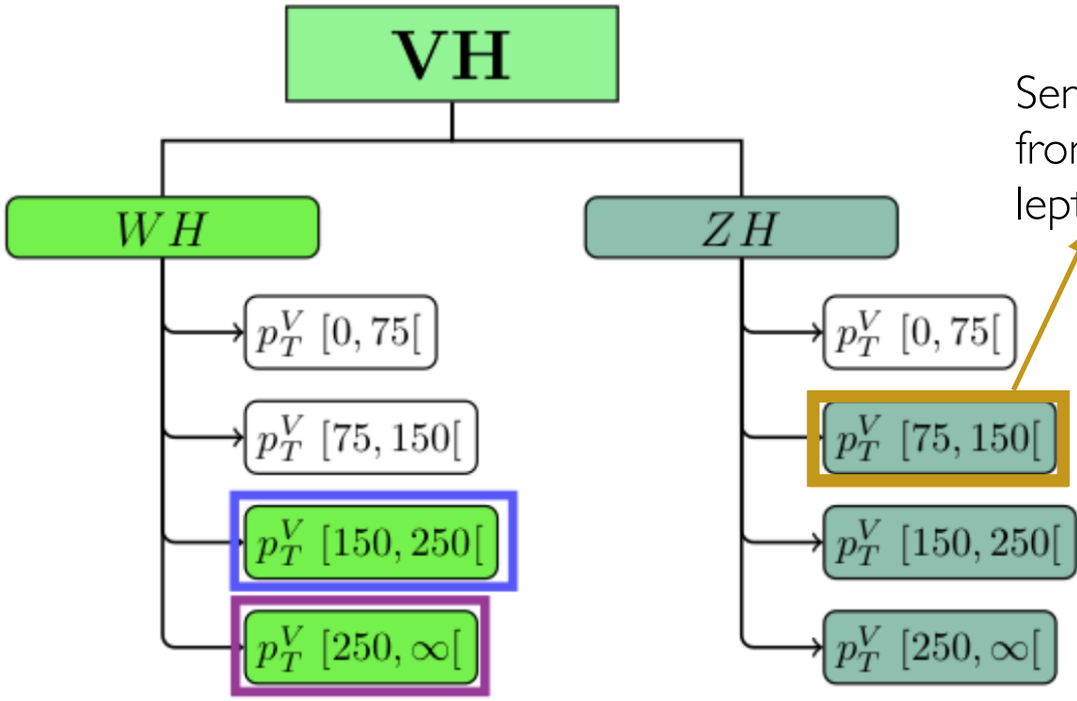
Leading sensitivity from VH→bb

- The result is the **observation** of VH production at 5.3σ (4.8σ expected).

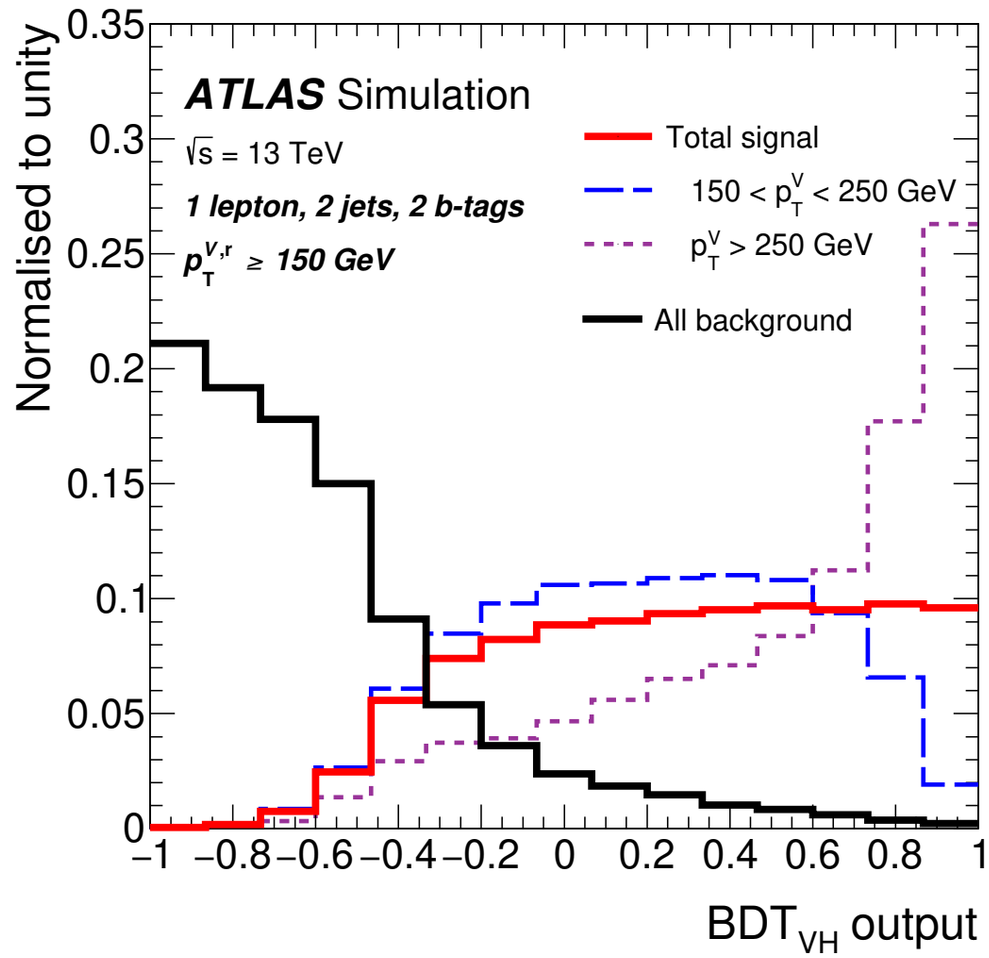
Measurement of the VH→bb production as a function of the vector-boson transfer momentum

VH→bb differential measurement

- After the observation of the VH production: differential measurement.
- Definition of five **fiducial differential cross section regions** (STXS framework) according to p_T of the W/Z boson:

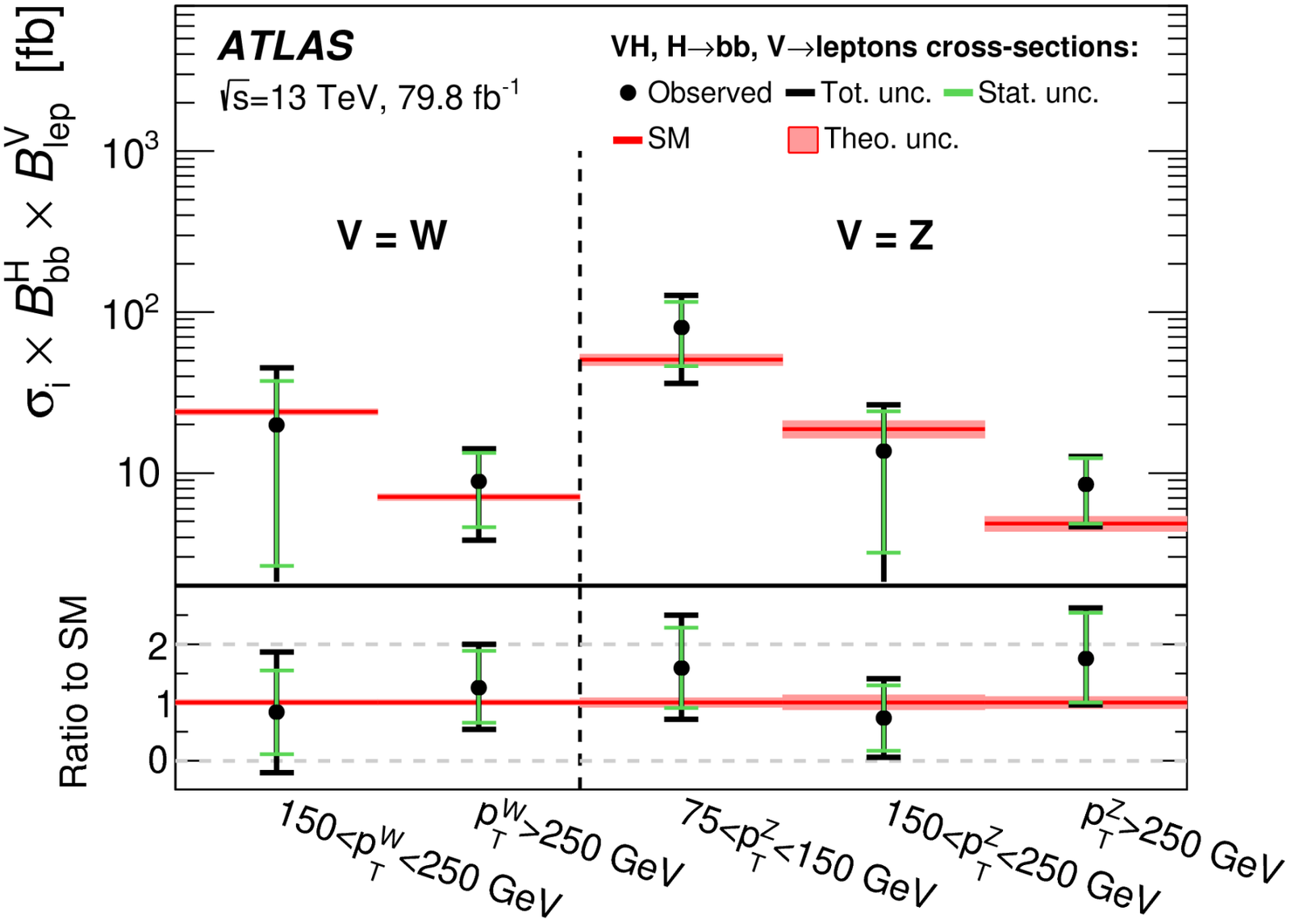


Sensitivity only from the 2 lepton channel



- Analysis strategy kept the same as the "observation analysis" (event selection, MVA training..)
- p_T^V regions potentially sensitive to **BSM** physics.

Measured cross-sections

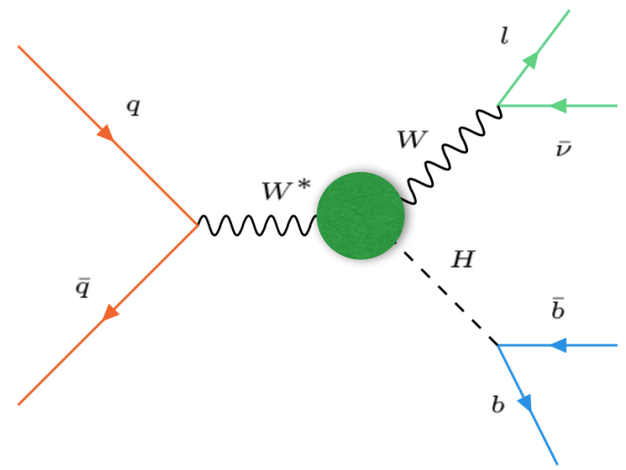


Results compatible with the Standard Model

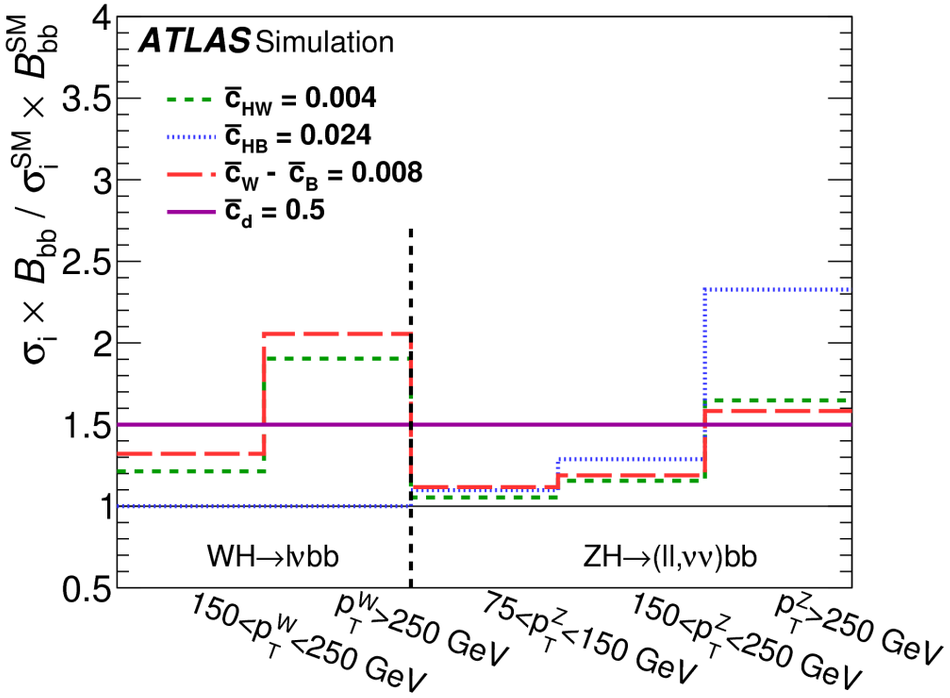
Effective Field Theories

- The SM Lagrangian can be expanded with an Effective Field Theory parametrisation:

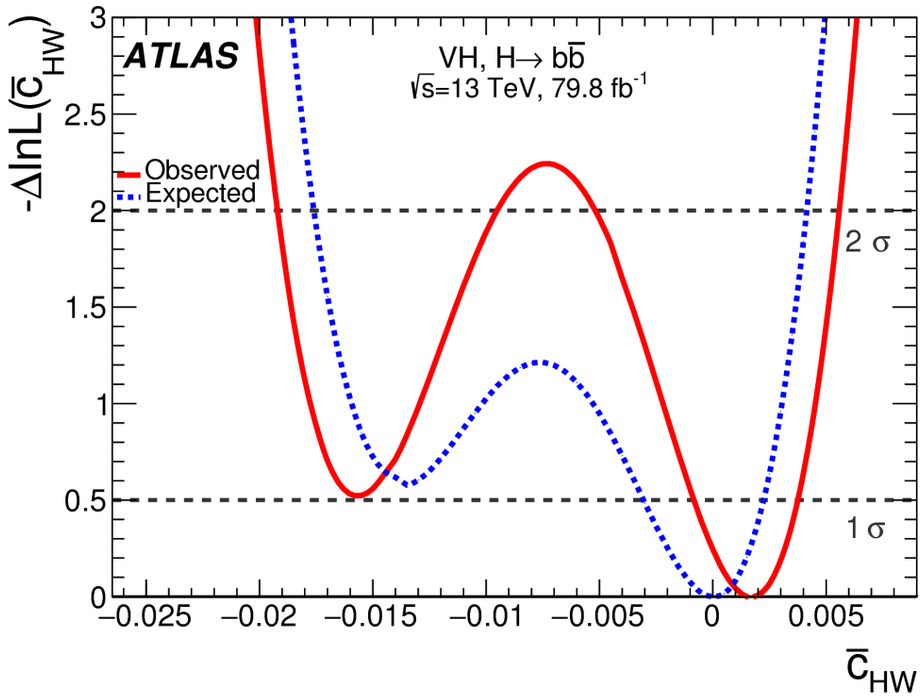
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i c_i^{(6)} \mathcal{O}_i^{(6)} / \Lambda^2$$



- The cross-sections measured are particularly sensitive to these new **coefficients**:



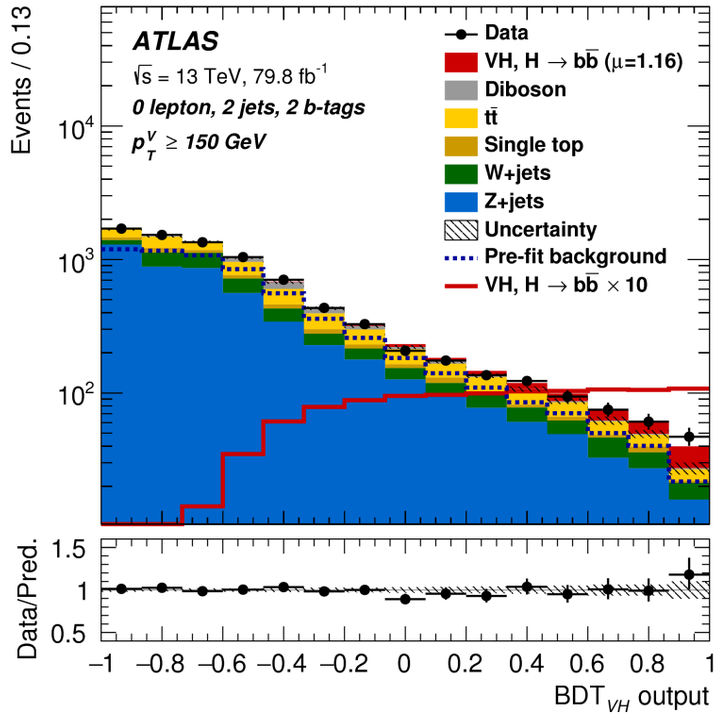
- 1-D fits of the coefficients have been performed (e.g. C_{HW}):



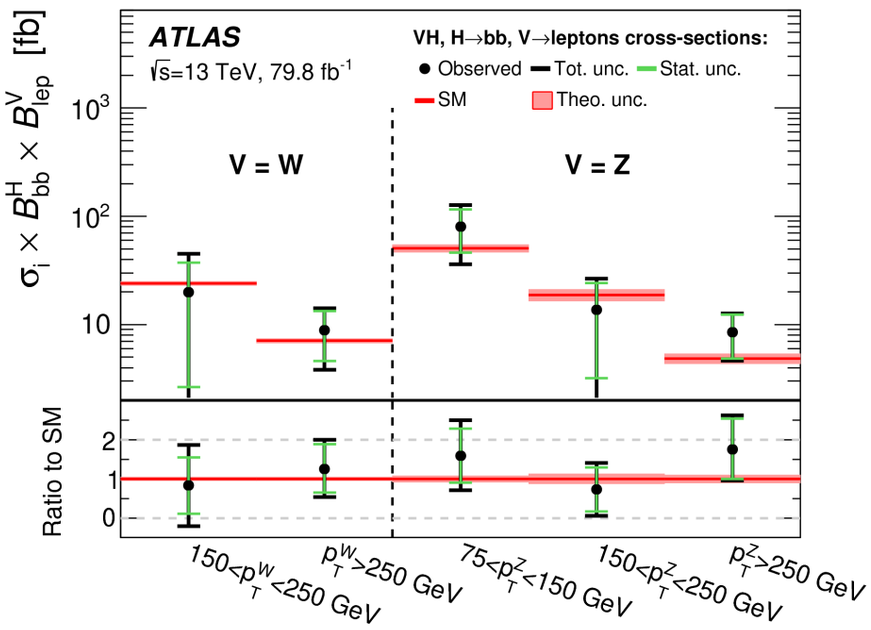
Conclusions

- H→bb decays at 5.4**σ** (5.5**σ** expected) have been **observed** with the ATLAS detector:

$$\mu_{H\to b\bar{b}} = \frac{\sigma_{obs}}{\sigma_{SM}} = 1.01^{+0.20}_{-0.20}$$



- First VH→bb **differential cross-section measurement** has been performed.



- All the measurements are consistent with the Standard Model.

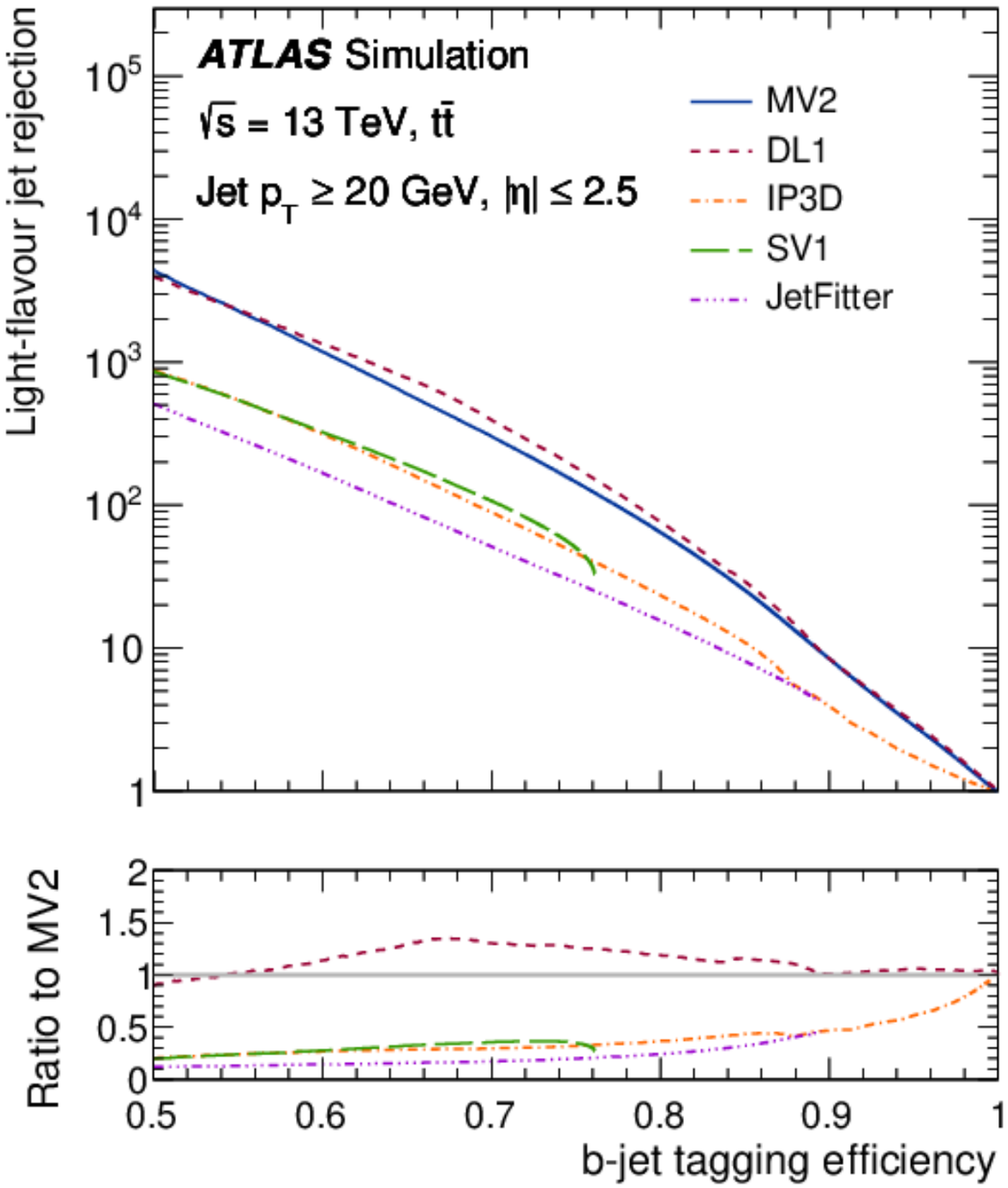
Thank you for your attention

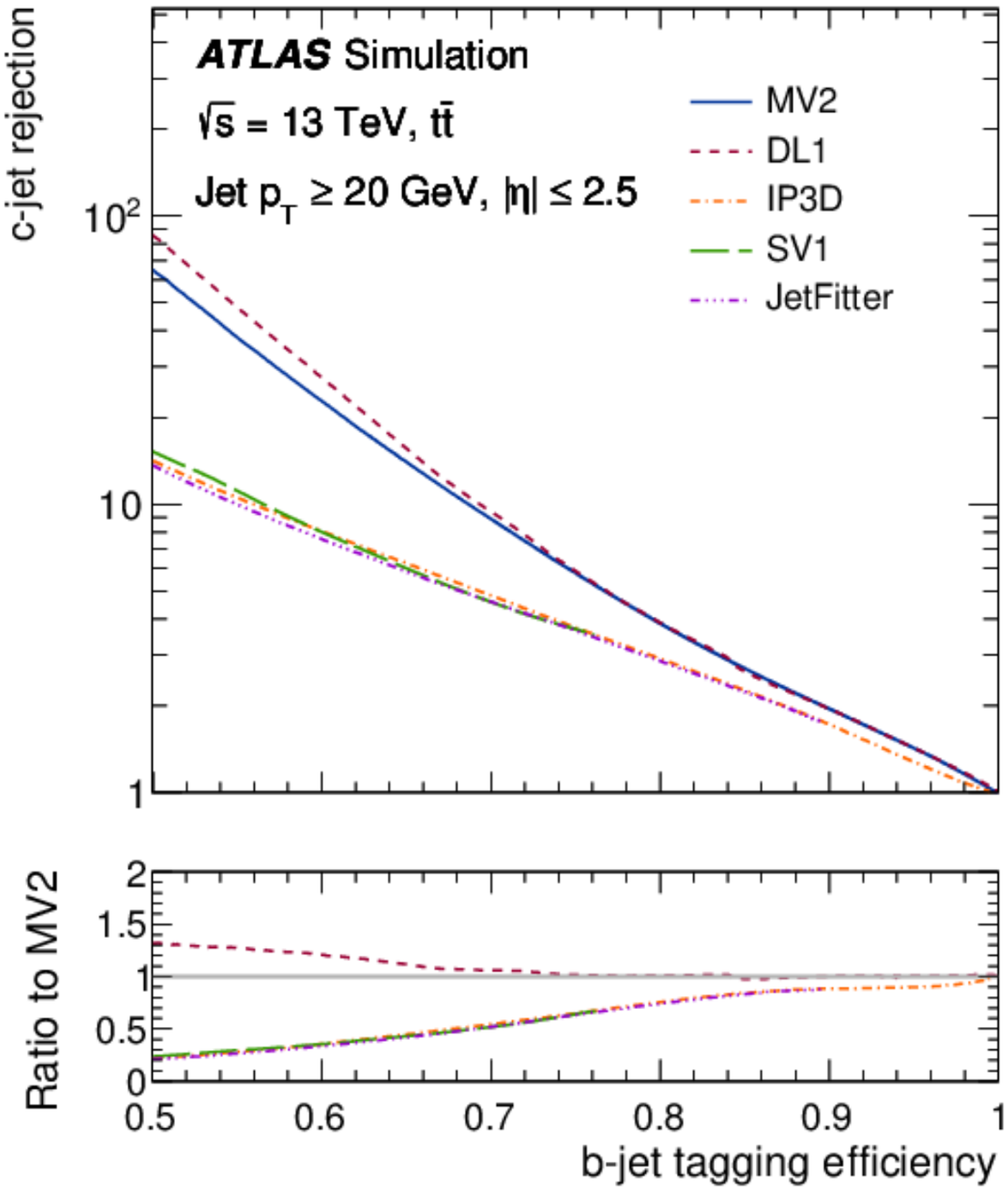
Backup

Detailed 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)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{b}\vec{b})$	$> 120^\circ$	–		–
$\Delta\phi(\vec{b_1}, \vec{b_2})$	$< 140^\circ$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–		–
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

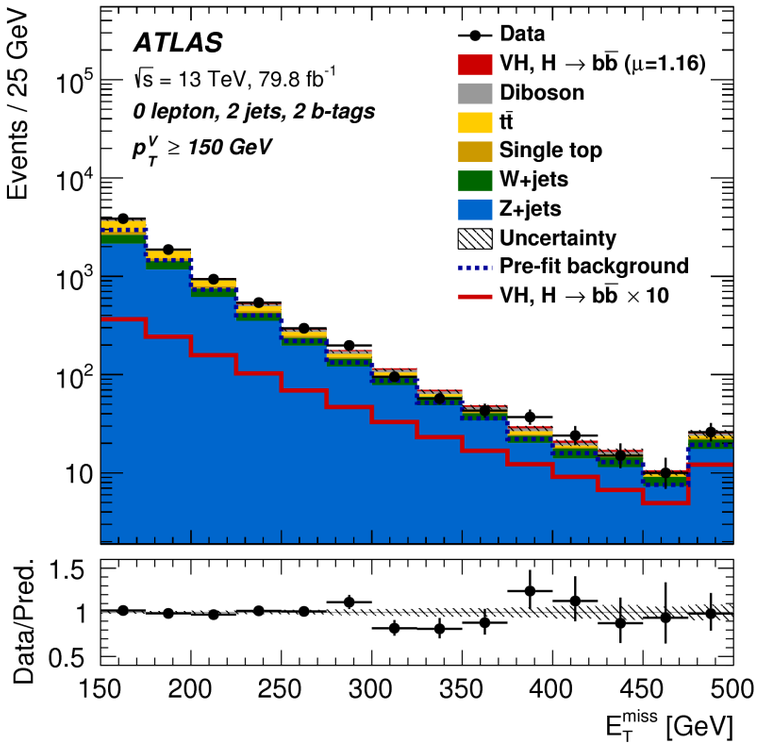
B-tagging efficiency Vs Light-/C-rejection



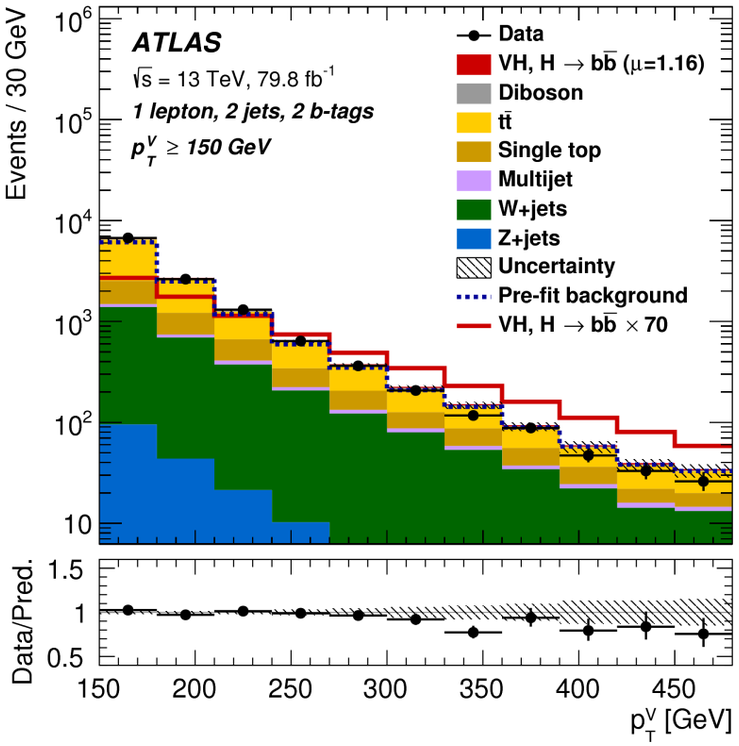


p_T^V and MET

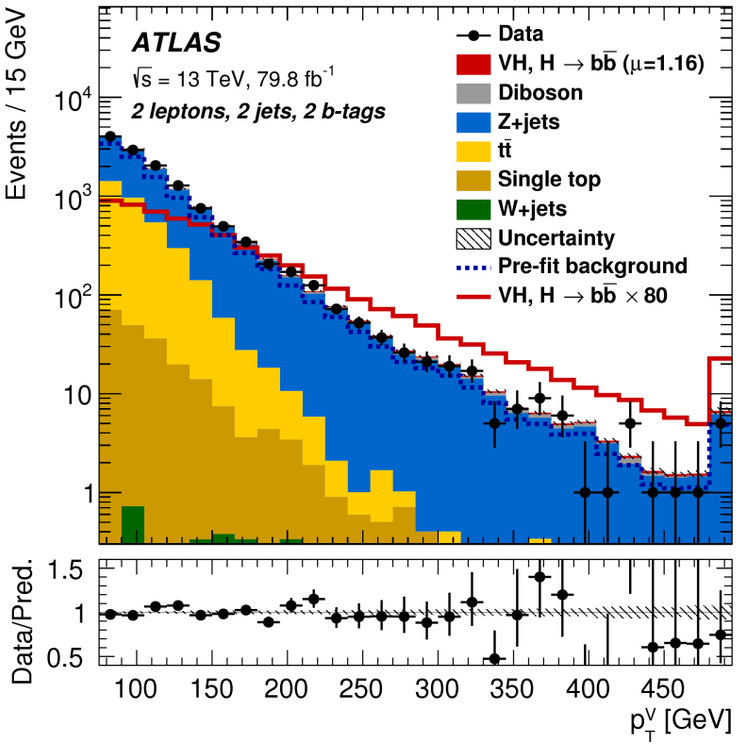
- 2 b-jets.
- *0 additional jets.*



0 Lepton Channel

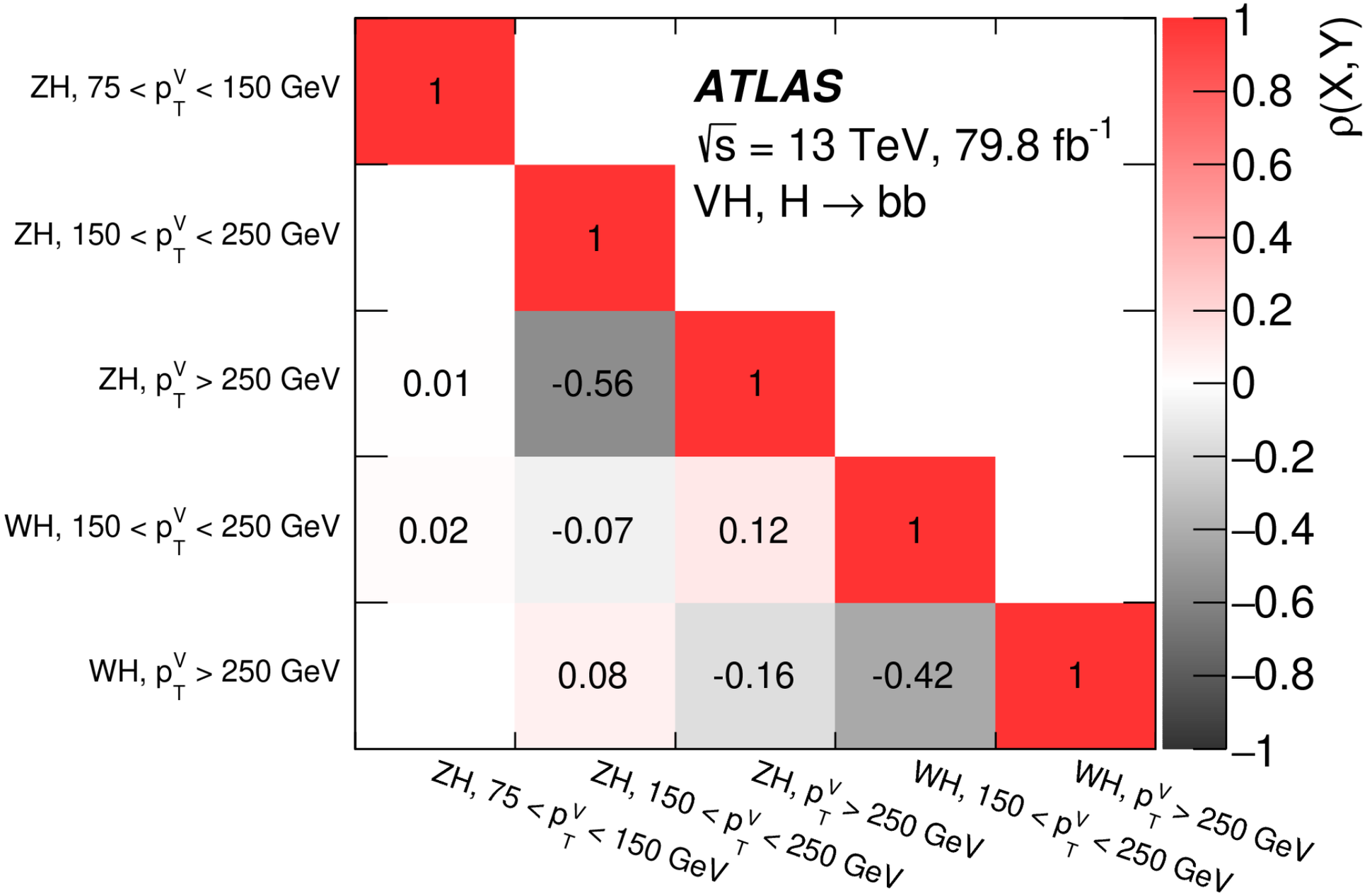


1 Lepton Channel



2 Lepton Channel

Correlation matrix STXS fit (5 POI)



EFT coefficients 1D fits

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])