Higgs Hunting 2022, September 12th 2022

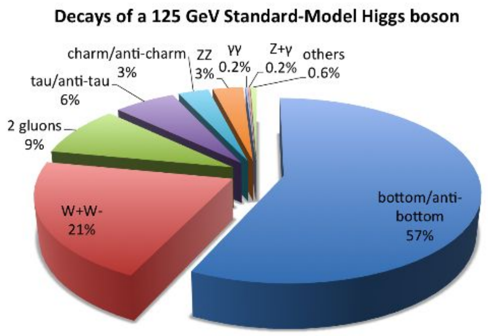
Studying the coupling of the Higgs boson to fermions with the ATLAS experiment

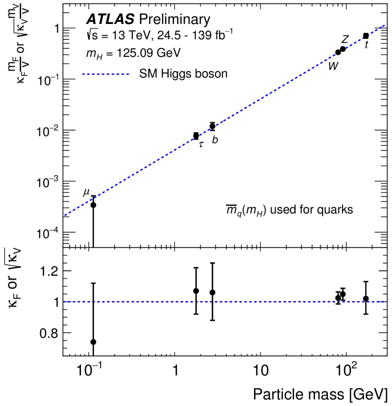
G. Callea on behalf of the ATLAS collaboration

Introduction

Measurements of the Higgs coupling to fermions (~70%) provide stringent tests to the Standard Model, as the Yukawa sector offers no fundamental insight into the fermion mass hierarchy

Higgs to third generation fermion couplings ***observed*** (different production modes studied)





N.B. LFV measurements not covered here. See presentation by [Yuan-Tang Chou]

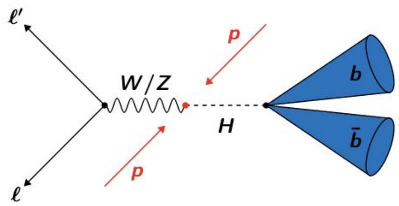
VH(bb) combination

ATLAS-CONF-2021-051

VH, H → bb extensively studied using full Run 2 dataset with complementary p_T^H acceptance

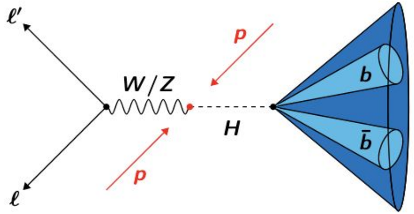
EPJC 81 (2021) 178

Resolved

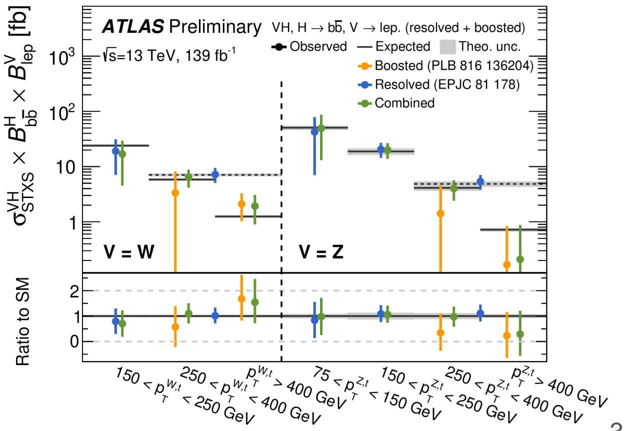


PLB 816 (2021) 1304

Boosted



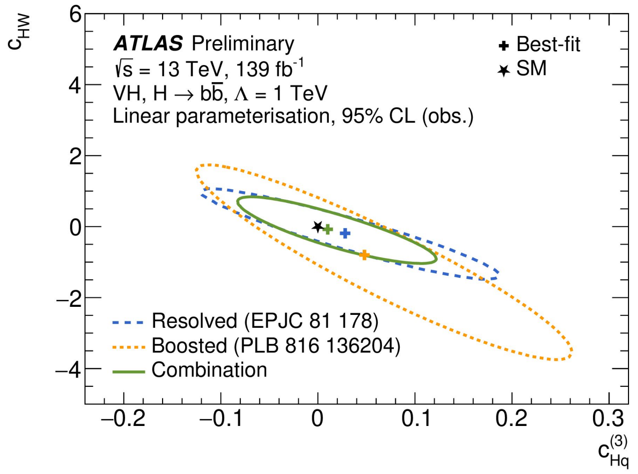
- Significant overlap between the two analyses
- Combined using p_T^V > 400 GeV events for boosted only
- STXS measurement in 7 bins
- Good agreement with SM predictions

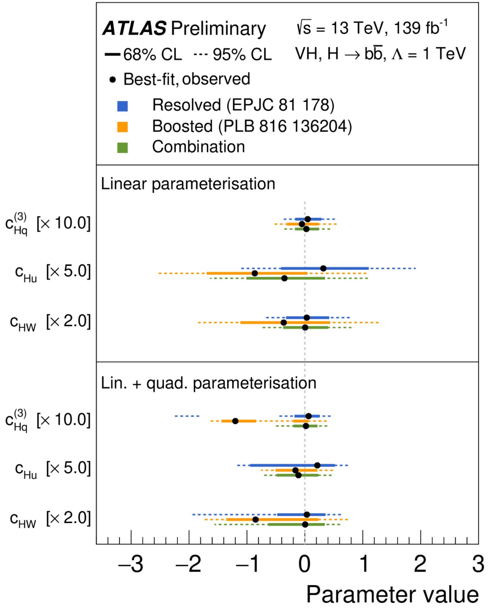


VH(bb) combination: EFT interpretation

ATLAS-CONF-2021-051

STXS p_T^V measurements interpreted in terms of a SM effective lagrangian (SMEFT) considering D = 6 operators





Constraints on Wilson coefficients sensitive to modifying VH, H → bb production are placed at 95% CL (either 1 or 2 POI fits)

Wilson coefficients are consistent with the SM predictions

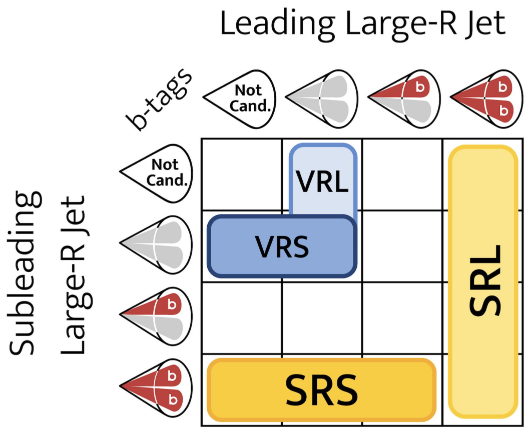
Combination strengthens limits w.r.t. individual analyses

Boosted H -> bb all-hadronic

PRD 105 (2022) 092003

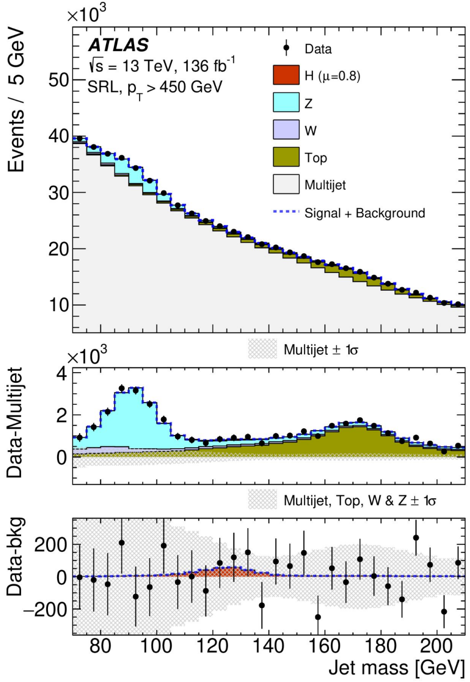
Targeting a highly boosted Higgs ($p_T^H > 450$ GeV) recoiling against a jet

- Select 2 large-R jets
- One containing 2 b-tagged track-jets
- Large background from multi-jet production
- Event categorisation:
  - **SR**: SRL (SRS) where the lead (sub-lead) jet is double b-tagged
  - **VR**: To study V+jet and multi-jet (modelled using a parametric function) models
  - **CR**: To study top events



Boosted H -> bb all-hadronic

PRD 105 (2022) 092003

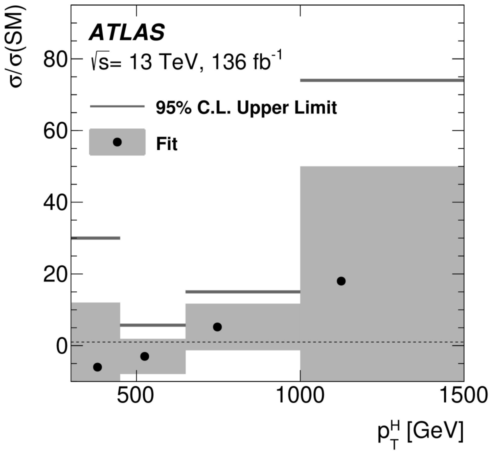


- Higgs candidate jet mass is the final discriminant
- Z(bb)+jets production used to validate the analysis
- Profile likelihood fit to extract the signal strength

Result	μ_H	μ_Z	$\mu_{t\bar{t}}$
Expected	1.0 ± 3.2	1.00 ± 0.17	1.00 ± 0.07
Observed	0.8 ± 3.2	1.29 ± 0.22	0.80 ± 0.06

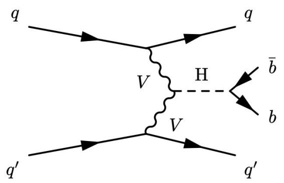
4 STXS bins

First cross-section measurement in high p_T^H region



VBF, H->bb analyses

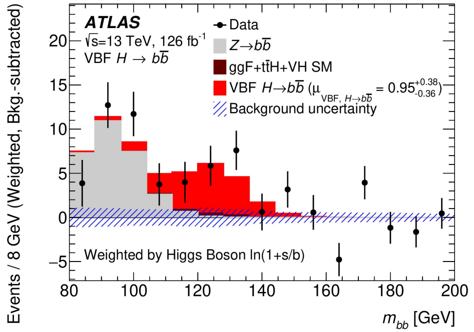
Search for H->bb decays in VBF events with 126 - 132 fb^{-1} of Run2 data

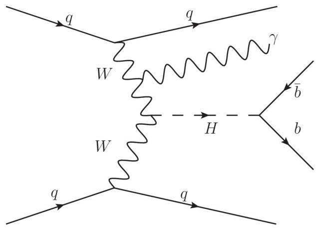


All-hadronic

- Select events with 2 central b-tagged and 2 VBF-like jets
- BDT and ANNs trained to aid the signal/background discrimination and define the analysis categories

[EPJC 81 (2021) 537]

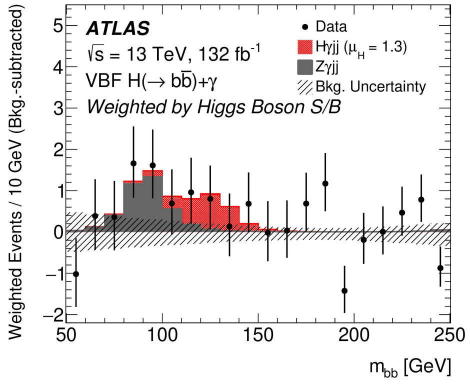




VBF+photon

- Similar strategy as the all-hadronic with requirements on an isolated photon
- The presence of the photon enriches the VBF purity

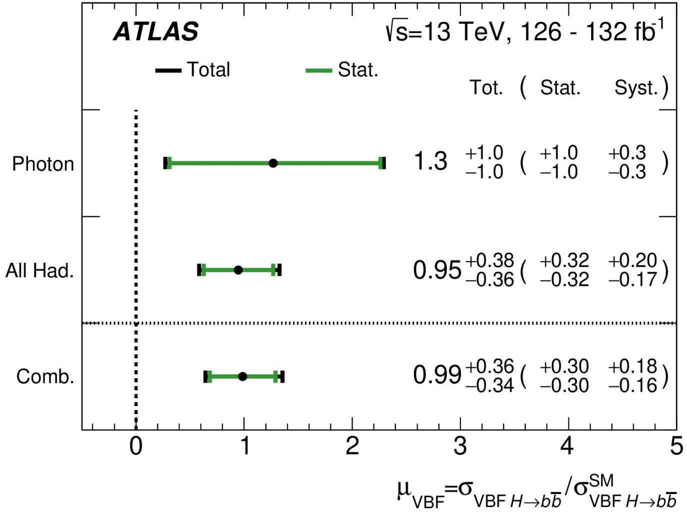
[JHEP 03 (2021) 268]



VBF, H->bb analyses

The signal strength measurements are statistically combined

- Both analyses are limited by the statistical unc.
- Sensitivity driven by the all-hadronic channel
- H->bb decay established at 3$\boldsymbol{\sigma}$ (exp. and obs) in VBF alone

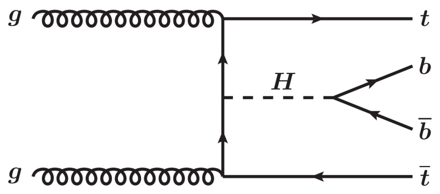


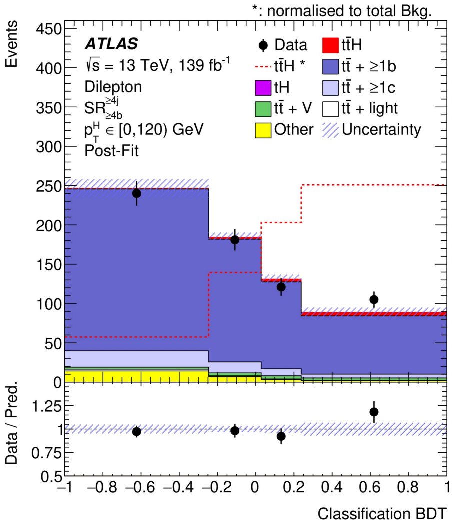
ttH(bb) analysis

[JHEP 06 (2022) 097]

The strongest Yukawa coupling can be probed directly with ttH production

- Selecting events with one or two leptonically decaying tops
- Events classified according to the number of leptons, jets and b-jets
- Machine learning techniques to aid the signal/background discrimination
- tt+jets is the dominant background





Dedicated ttH(bb) talk by [Neelam Kumari]

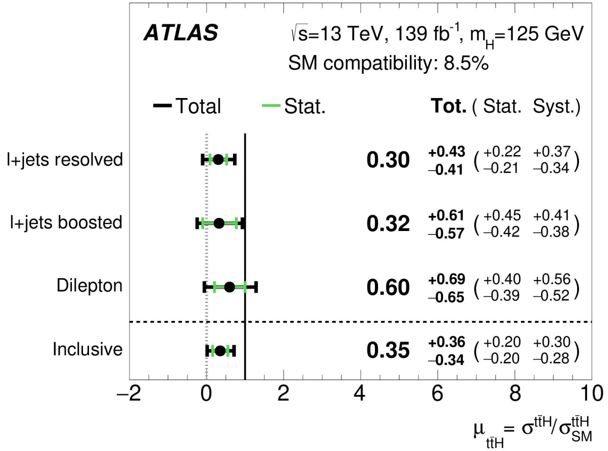
ttH(bb) analysis

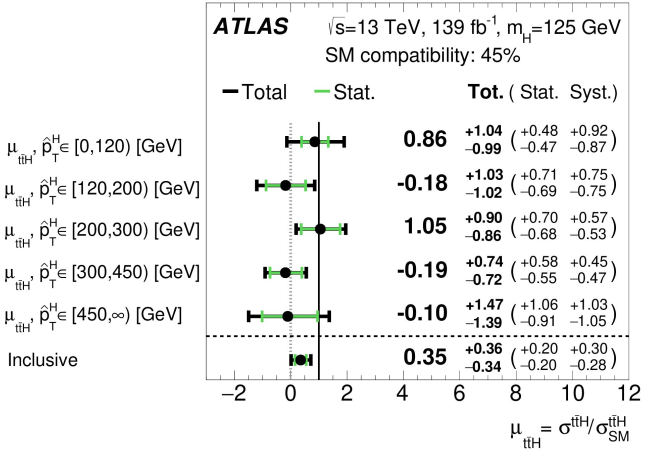
JHEP 06 (2022) 097

Profile likelihood fit to extract μ_{ttH}

Boosted category in p_T^H > 300 GeV (single-lep channel)

Cross section measurement in 5 STXS bins defined by the p_T^H





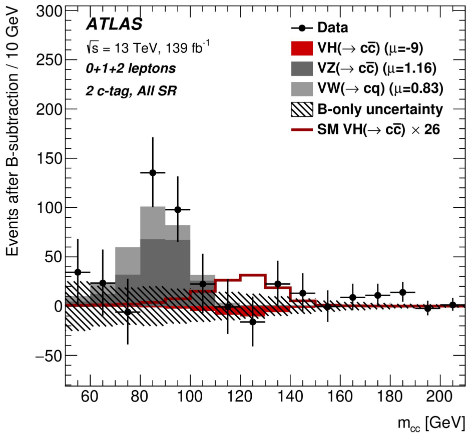
VH, H->cc

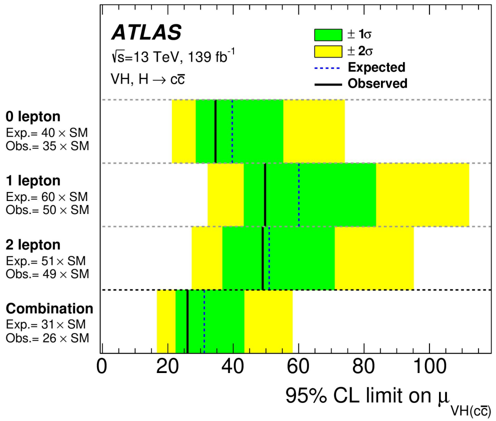
EPJC 82 (2022) 717

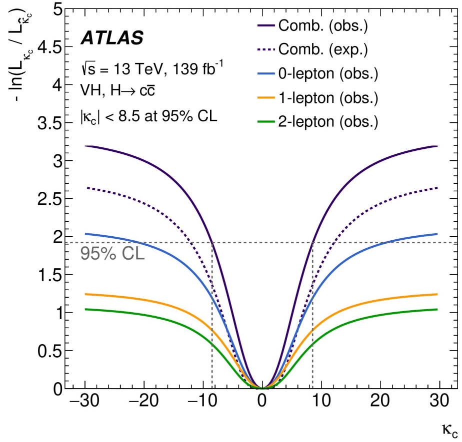
Offers a unique chance to directly probe the coupling of the Higgs boson to the 2nd generation quarks

- Optimised c-jet tagger with b-jet veto
- Analysis strategy validated with diboson analyses
- Stat. and syst uncertainties of the same magnitude

Constraint on k_c when all the other Higgs couplings are SM-like is set to $|k_c| < 8.5$ @ 95% CL



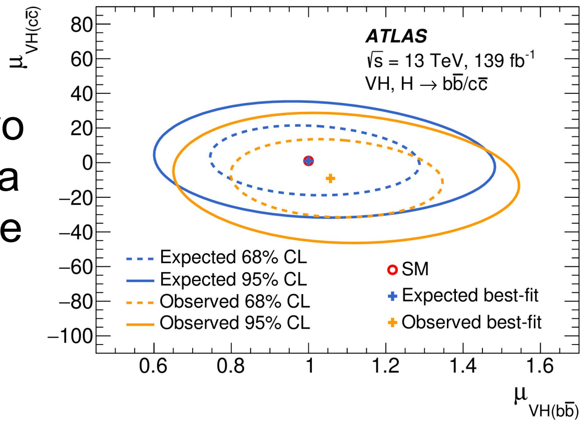


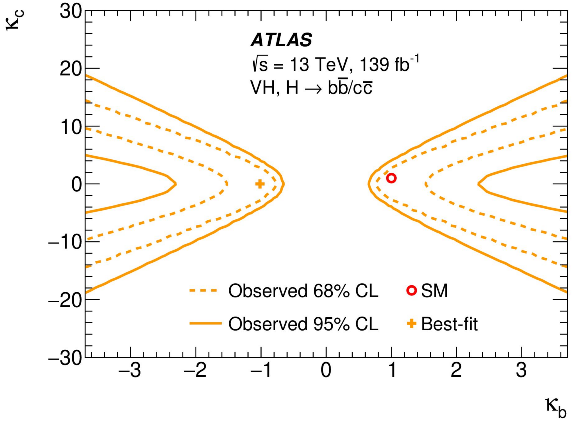


VHbb/cc combination

EPJC 82 (2022) 717

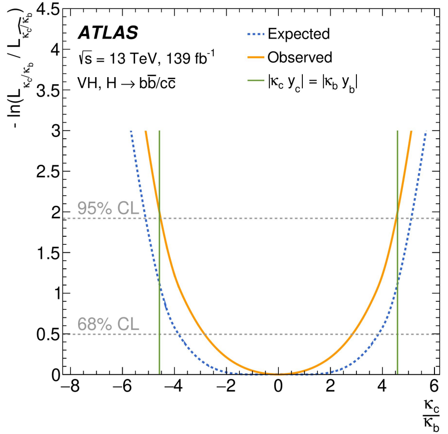
Although the SR of the two analyses are orthogonal, a small overlap occurs in the CRs





$|k_c/k_b| < 4.5$ @ 95% CL (without any assumptions on the Higgs boson width)

Higgs-charm coupling is weaker than Higgs-bottom coupling @ 95% CL



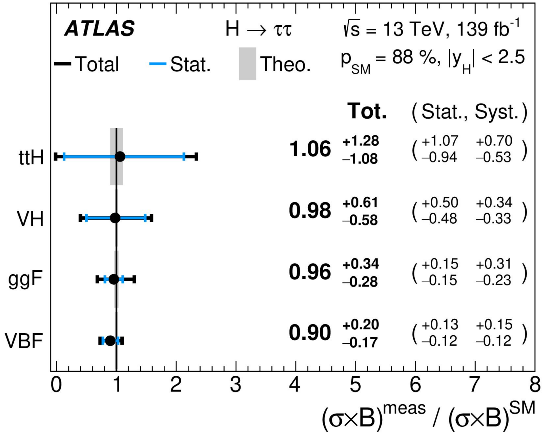
H -> $\tau\tau$ analysis

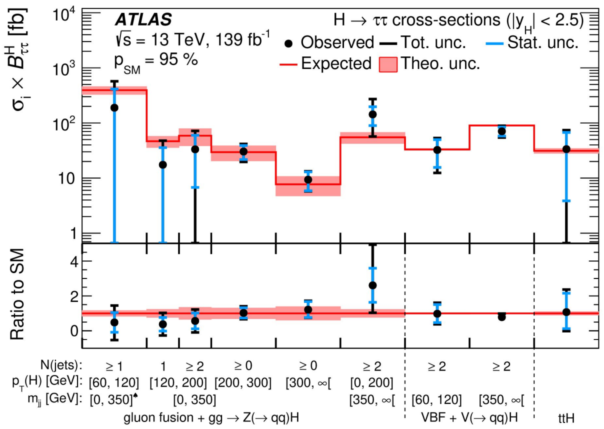
JHEP 08 (2022) 175

Most sensitive probe of Higgs boson coupling to leptons (2nd most copious fermionic decay)

- Analysis targets four production modes
- Dominant background from Z-> $\tau\tau$ events (MVA used to enhance the discrimination)
- Z-> $\tau\tau$ normalisation determined from Z -> ll data samples with the "kinematic embedding" technique

Missing Mass Calculator algorithm used to improve the $\tau\tau$ mass resolution to account for neutrino energy losses





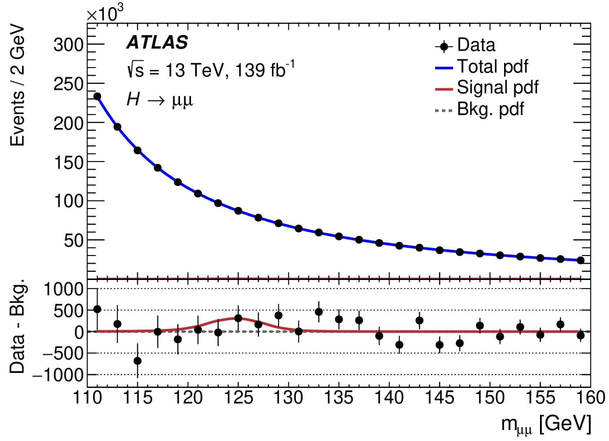
Inclusive H -> $\tau\tau$ cross section measured with a precision of 13%, and 9 STXS bins were measured

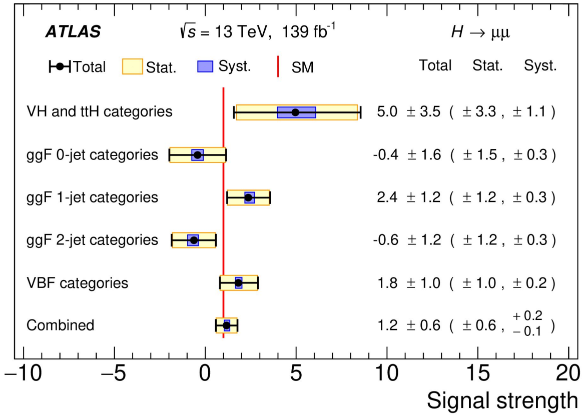
H -> $\mu\mu$ analysis

PLB 812 (2021) 135980

Most promising probe of Higgs coupling to 2nd generation fermions

- Z->$\mu\mu$ is the dominant background
- BDTs are trained in each exclusive signal region targeting different production modes
- Sensitivity driven by VBF targeted categories. Very statistically limited





- Observed (expected) significance of 2.0 (1.7) σ (wrt background only)
- Approaching sensitivity to test the SM predictions
- One of the most important topics for Run3

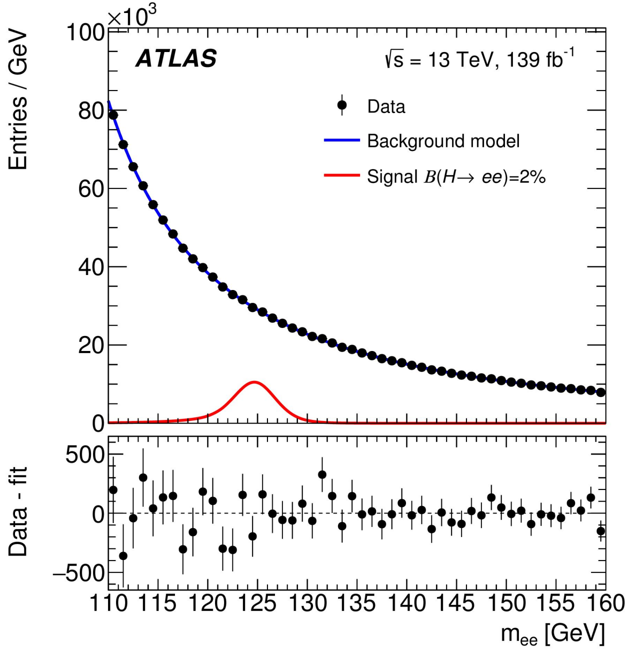
H -> ee analysis

PLB 801 (2020) 135148

Directly probes the magnitude of y_e

Similar analysis strategy to H-> $\mu\mu$

- Main background from DY process
- Binned likelihood fit in the 110-160 GeV region of m_{ee}
- Observed (expected) limit at 95% CL:
    - $BR_{H\to ee} < 3.6\ (3.5) \times 10^{-4}$



LFV H->eμ studied in the paper as well

Summary

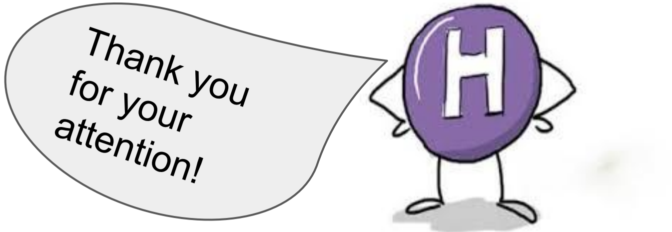
ATLAS Run2 analyses improved our understanding of the Higgs boson’s coupling to fermions

Couplings to the third generation fermions are well established!

Exciting progress on the coupling to second generation fermions:

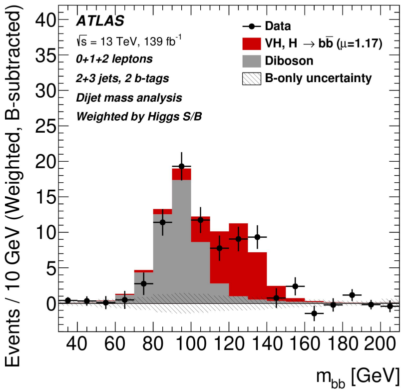
- H -> $\mu\mu$ is approaching the level at which the SM predictions can be tested
- The search for H -> cc has tighten up the constraints on k_c

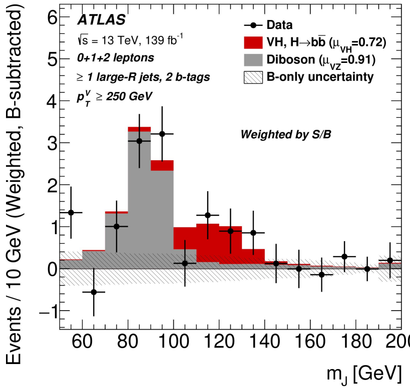
Looking forward to having new datasets to study the fermion couplings!

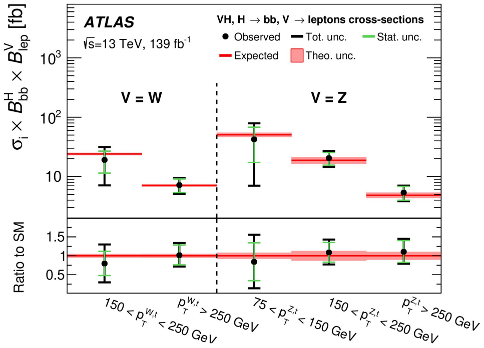


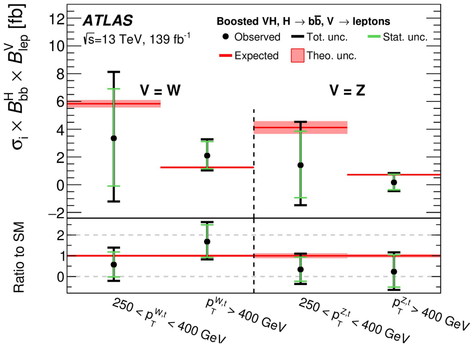
Backup

VHbb resolved and boosted

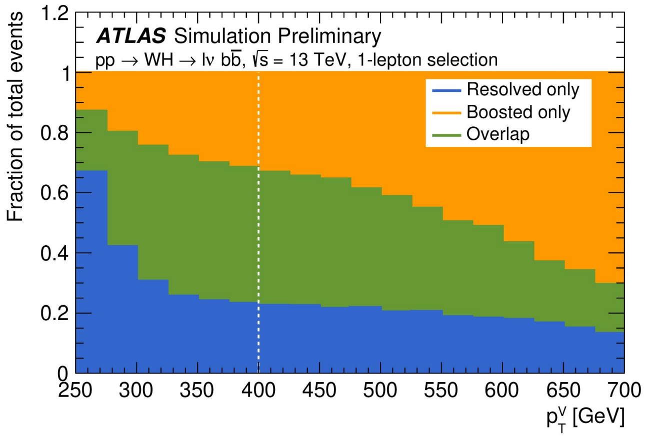


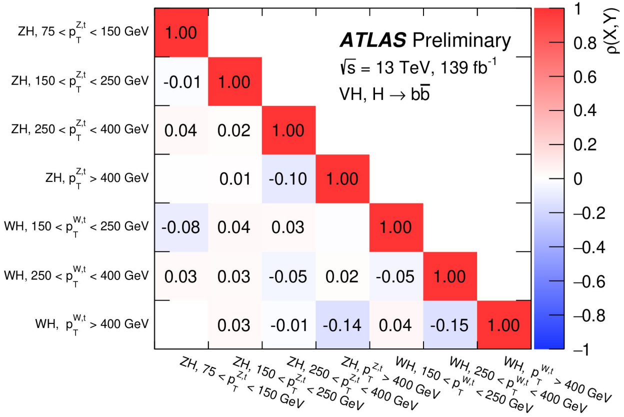




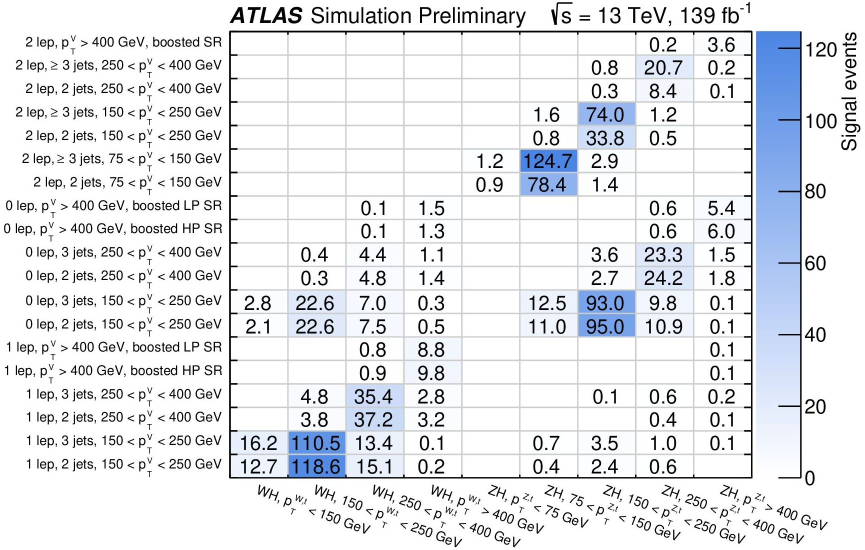


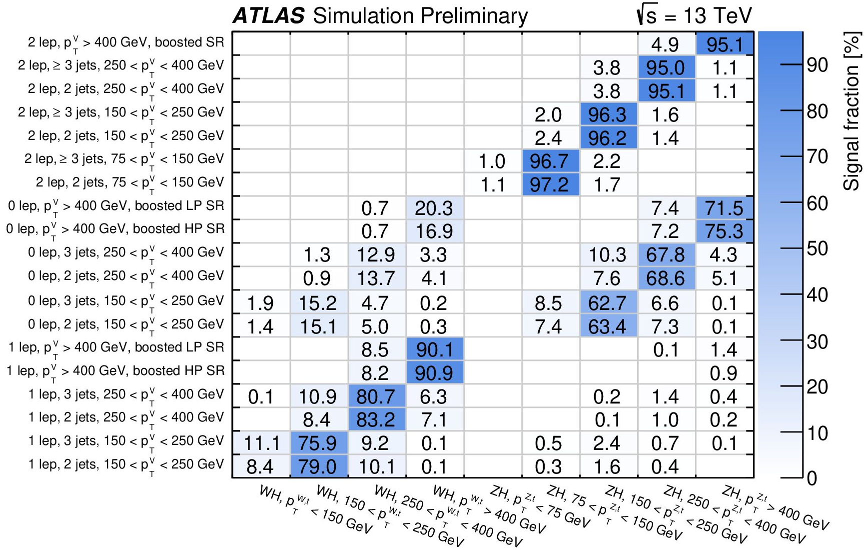
VHbb combination





VHbb combination





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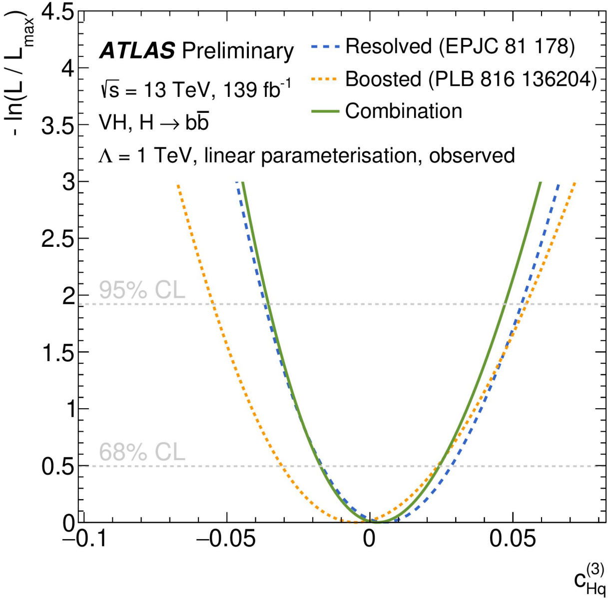
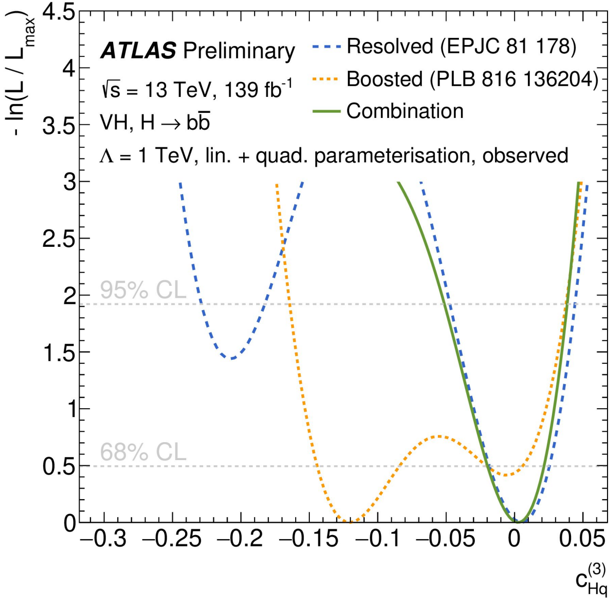




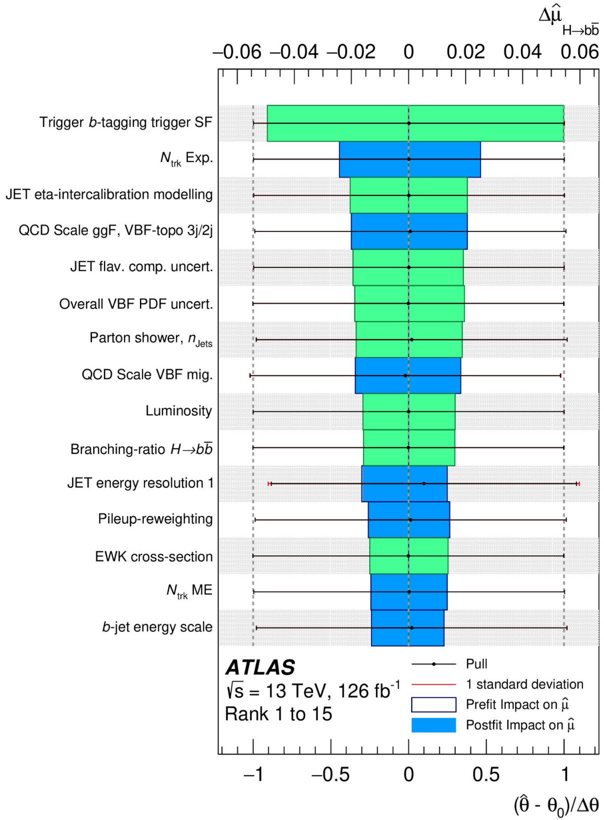
Boosted Hbb all-hadronic

Process	Jet p_{T} range [GeV] 250–450	450–650	650–1000	> 1000
		SRL		
ggF	–	0.56	0.50	0.39
VBF	–	0.17	0.16	0.17
VH	–	0.14	0.18	0.25
$t\bar{t}H$	–	0.13	0.16	0.19
		SRS		
ggF	0.28	0.46	0.43	–
VBF	0.07	0.19	0.21	–
VH	0.26	0.24	0.26	–
$t\bar{t}H$	0.39	0.11	0.10	–

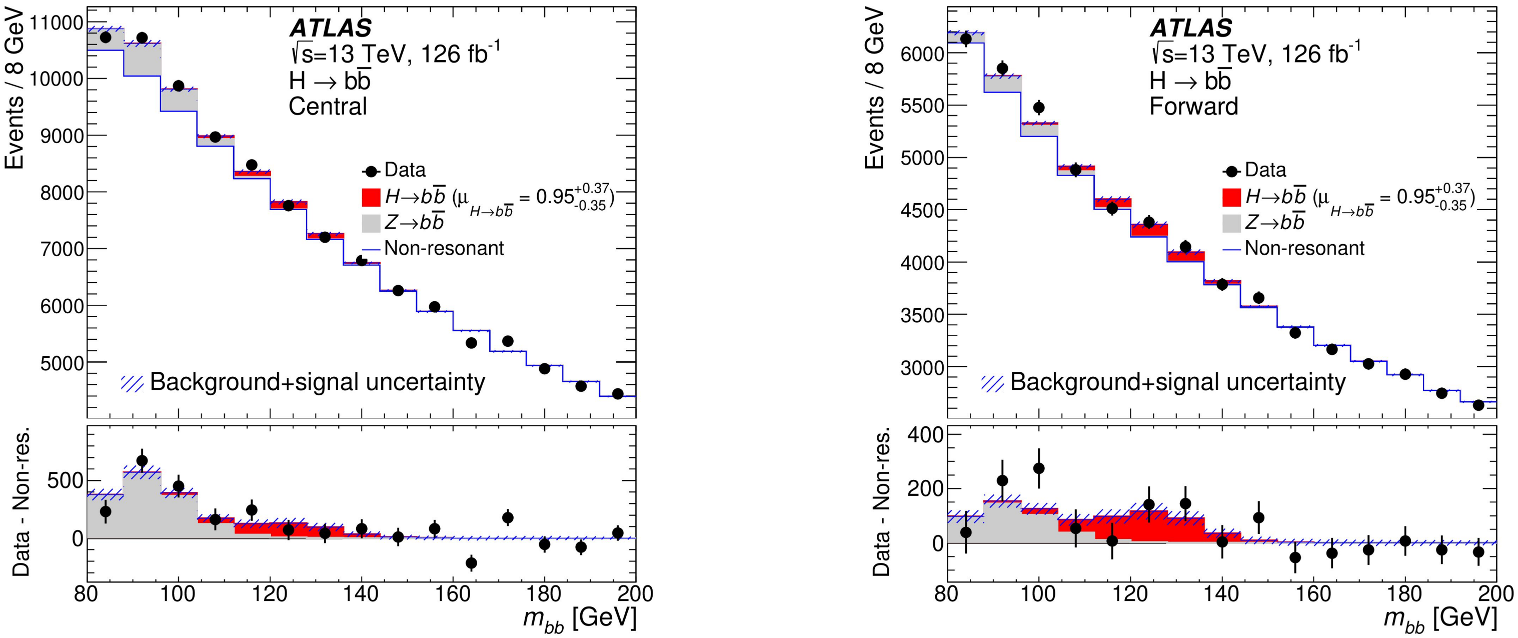
Uncertainty Contribution	$p_{\mathrm{T}}^{H} > 450$ GeV
Total	3.5
Statistical	2.6
Systematic	2.3
Jet systematic uncertainties	2.2
Modeling and theory systs.	0.8
Flavor-tagging systs.	0.2

VBF H->bb all-hadronic

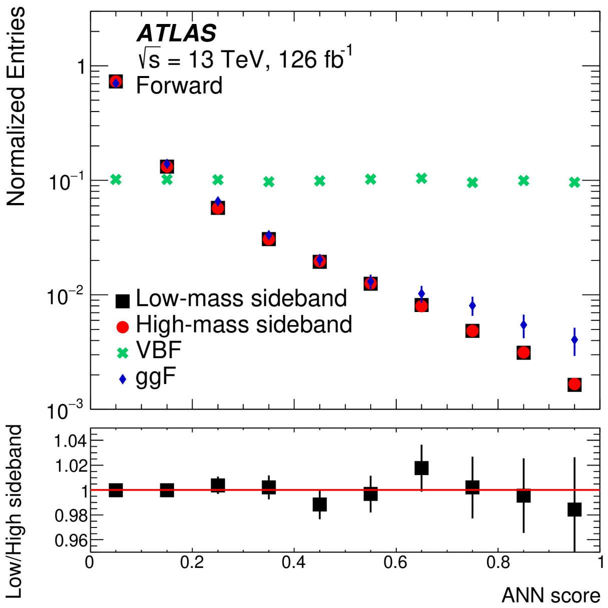
Uncertainty	$\sigma(\mu_{\mathrm{VBF},H\to b\bar{b}})$
Statistics	± 0.32
NR Background Bias	± 0.15
Embedded Z	± 0.05
Experimental	$+0.10/-0.06$
Trigger	$+0.07/-0.03$
Jet	$+0.07/-0.04$
Flavor Tagging	$+0.02/-0.01$
Other	$+0.03/-0.02$
Signal Theory	$+0.06/-0.03$

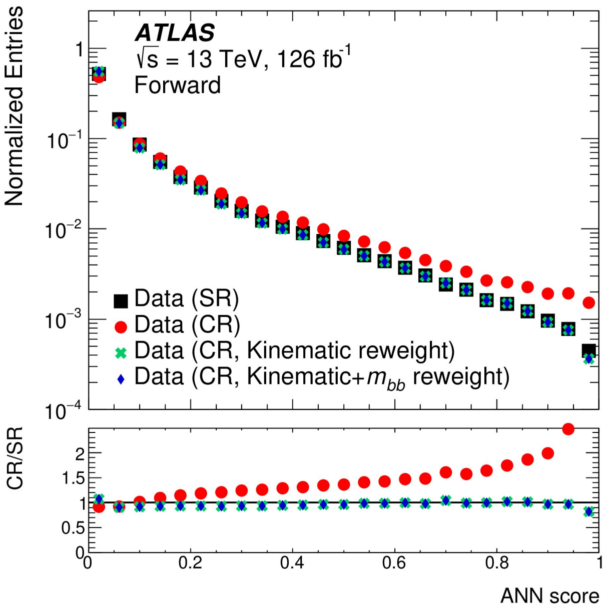


VBF, H->bb all-hadronic



VBF, H->bb all-hadronic

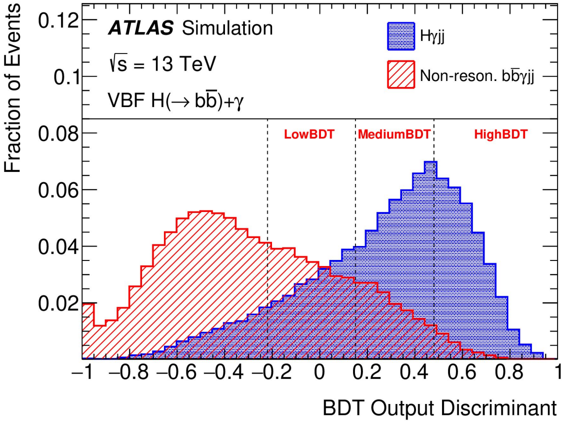


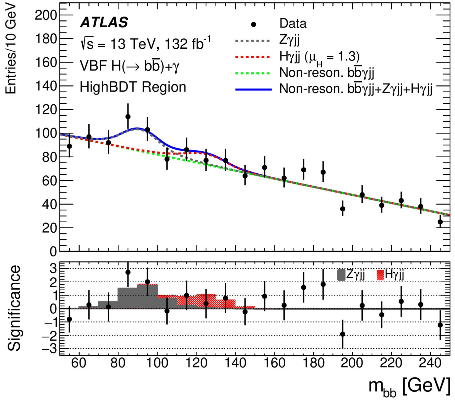


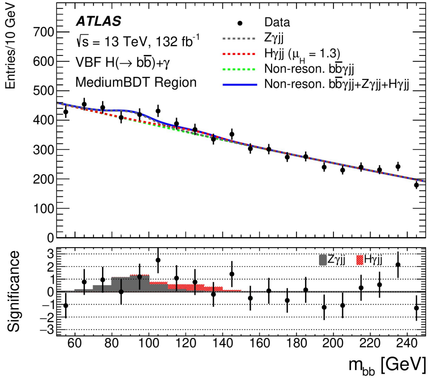
VBF, H->bb + photon

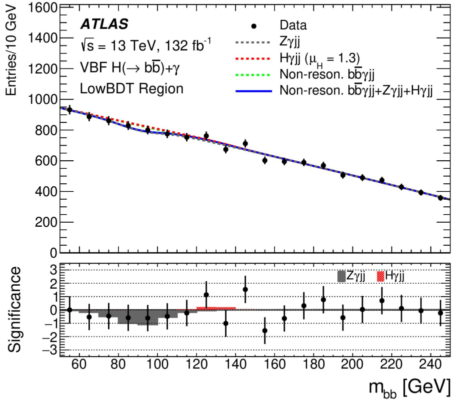
Source of absolute uncertainty	$\sigma(\mu_H)$ down	$\sigma(\mu_H)$ up
Statistical		
Data statistical	-0.78	$+0.80$
Bkg. fit shapes	-0.19	$+0.22$
Bkg. fit normalizations	-0.51	$+0.52$
Z boson normalizations	-0.15	$+0.14$
Systematic		
Spurious signal	-0.24	$+0.21$
Theoretical	-0.01	$+0.08$
Photon	-0.01	$+0.03$
Jet	-0.06	$+0.20$
b-tagging	-0.02	$+0.11$
Auxiliary	-0.01	$+0.04$
Total	-0.99	$+1.04$
Total statistical	-0.96	$+0.99$
Total systematic	-0.25	$+0.32$

VBF, H->bb + photon









H-> $\tau\tau$

Criteria	$\tau_e\tau_\mu$	$\tau_{\text{lep}}\tau_{\text{had}}$		$\tau_{\text{had}}\tau_{\text{had}}$
		$\tau_e\tau_{\text{had}}$	$\tau_\mu\tau_{\text{had}}$	
$N(e)$	1	1	0	0
$N(\mu)$	1	0	1	0
$N(\tau_{\text{had-vis}})$	0	1	1	2
$N(b\text{-jets})$	0 (85% WP)	0 (85% WP)	0 (85% WP)	0 (70% WP) (≥ 1 or 2 in ttH categories)
$p_{\text{T}}(e)$ [GeV]	> 15 to 27	> 27		
$p_{\text{T}}(\mu)$ [GeV]	> 10 to 27.3		> 27.3	
$p_{\text{T}}(\tau_{\text{had-vis}})$ [GeV]		> 30		$> 40,\ 30$
Identification	e/μ: Medium	$e/\mu/\tau_{\text{had-vis}}$: Medium		$\tau_{\text{had-vis}}$: Medium
Isolation	e: Loose, μ: Tight	e: Loose	μ: Tight	
Charge	Opposite charge			
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 20			
Kinematics	$m_{\tau\tau}^{\text{coll}} > m_Z - 25\,\text{GeV}$ $30\,\text{GeV} < m_{e\mu} < 100\,\text{GeV}$	$m_{\text{T}} < 70\,\text{GeV}$		
Leading jet	$p_{\text{T}} > 40\,\text{GeV}$			$p_{\text{T}} > 70\,\text{GeV},\ \lvert\eta\rvert < 3.2$
Angular	$\Delta R_{e\mu} < 2.0$ $\lvert\Delta\eta_{e\mu}\rvert < 1.5$	$\Delta R_{\ell\tau_{\text{had-vis}}} < 2.5$ $\lvert\Delta\eta_{\ell\tau_{\text{had-vis}}}\rvert < 1.5$		$0.6 < \Delta R_{\tau_{\text{had-vis}}\tau_{\text{had-vis}}} < 2.5$ $\lvert\Delta\eta_{\tau_{\text{had-vis}}\tau_{\text{had-vis}}}\rvert < 1.5$
Coll. app. x_1/x_2	$0.1 < x_1 < 1.0$ $0.1 < x_2 < 1.0$	$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.2$		$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.4$

H-> $\boldsymbol{\tau\tau}$

Embedding:

The kinematic properties of the Z boson are reconstructed with a much better resolution in the Z -> ll decay channel than in the Z -> $\tau\tau$ one due to the absence of neutrinos and the excellent momentum resolution of the ATLAS detector for electrons and muons.

The simplified embedding consists of a rescaling of the transverse momentum of each reconstructed lepton through parameterisation, followed by a recomputation of all the relevant kinematic quantities in the analysis.

H-> $\boldsymbol{\tau\tau}$

Missing Mass Calculator:

Advanced likelihood-based technique which relies on the information about the τ-lepton candidate momenta, the presence of additional jets, $E_{T,miss}$ and the type of τ-lepton decay

H-> $\tau\tau$

	Variable	VBF	V(had)H	ttH vs $t\bar{t}$	ttH vs $Z \to \tau\tau$
Jet properties	Invariant mass of the two leading jets	•	•		
	$p_{\mathrm{T}}(jj)$	•	•		
	Product of η of the two leading jets	•			
	Sub-leading jet p_{T}	•			
	Leading jet η				•
	Sub-leading jet η				•
	Scalar sum of all jets p_{T}			•	•
	Scalar sum of all b-tagged jets p_{T}				•
	Best W-candidate dijet invariant mass			•	•
	Best t-quark-candidate three-jet invariant mass			•	•
Angular distances	$\Delta\phi$ between the two leading jets	•			
	$\Delta\eta$ between the two leading jets	•	•		
	ΔR between the two leading jets		•		
	$\Delta R(\tau\tau, jj)$		•		
	$\Delta R(\tau, \tau)$		•	•	
	Smallest ΔR (any two jets)			•	
	$\lvert\Delta\eta(\tau, \tau)\rvert$			•	•
τ prop.	$p_{\mathrm{T}}(\tau\tau)$			•	
	Sub-leading τ p_{T}				•
	Sub-leading τ η				•
H cand.	$p_{\mathrm{T}}(Hjj)$	•	•		
	$p_{\mathrm{T}}(H)/p_{\mathrm{T}}(jj)$		•		
$\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$		•	•	•
	Smallest $\Delta\phi$ $(\tau, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$				•

H-> $\boldsymbol{\tau\tau}$

Source of uncertainty	Impact on $\Delta\sigma\,/\,\sigma(pp \to H \to \tau\tau)$ [%] Observed	Expected
Theoretical uncertainty in signal	8.7	8.5
Jet and $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$	4.5	4.2
Background sample size	4.0	3.7
Hadronic τ decays	2.1	2.1
Misidentified τ	2.0	2.0
Luminosity	1.8	1.8
Theoretical uncertainty in $Z+$jets processes	1.7	1.2
Theoretical uncertainty in top processes	1.1	1.1
Flavour tagging	0.4	0.5
Electrons and muons	0.4	0.4
Total systematic uncertainty	12.0	11.4
Data sample size	7.2	6.7
Total	13.9	13.2