Measurements of Higgs boson production and decay rates with the ATLAS experiment

Ricardo Barrué, on behalf of the ATLAS Collaboration

SFRH/BD/150792/2020

Motivation

Higgs rates are sensitive probes of physics beyond the Standard Model (BSM)

- From e.g. "new" heavy particles in loops

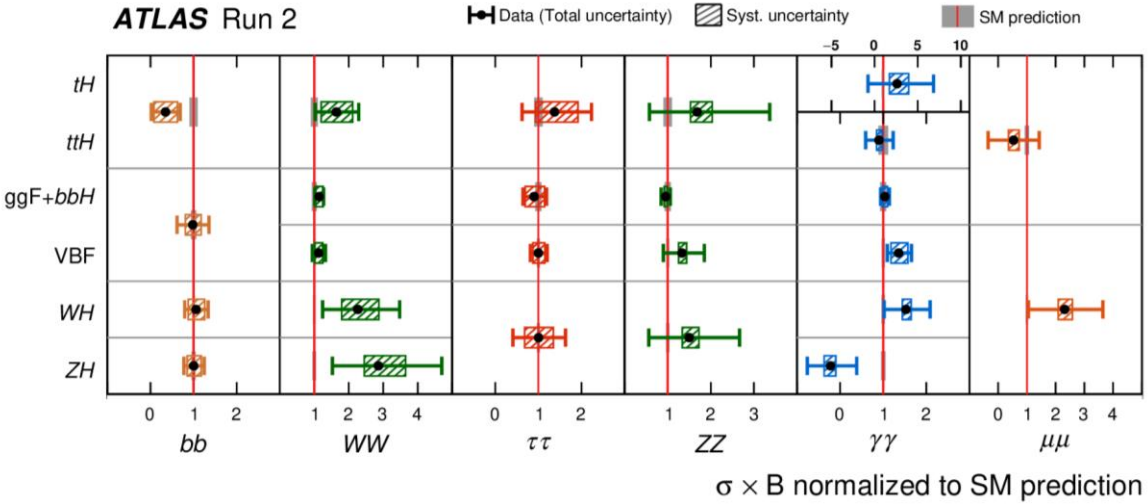
Largest dataset ever collected of Higgs bosons from pp collisions at $\sqrt{s}$ =13 TeV

- Best ever sensitivity to small deviations from new physics

New dataset at $\sqrt{s}$ =13.6 TeV, the highest energy ever achieved in pp collisions

- Can probe the growth of Higgs rates with $\sqrt{s}$ for new physics effects

Where we stand



Latest ATLAS/CMS combinations show that nature agrees remarkably well with the SM

- Nature 607, 52 (2022) (ATLAS) / Nature 607, 60 (2022) (CMS)

Outline

Full Run 2 (13 TeV, 140 fb^{-1})

1. VBF WH - arXiV:2402.00426
2. High-pT V(qq)H(bb) - Phys. Rev. Lett. 132, 131802 (2024)
3. $Z\gamma$ decay (ATLAS + CMS) - Phys. Rev. Lett. 132, 021803 (2024)
4. V(leptons)H($\tau\tau$) - arXiV:2312.02394
5. H($\tau\tau$) STXS - ATLAS-CONF-2024-007 **NEW !**

Run 3 (13.6 TeV, 31.4-29.0 fb^{-1}):

- Production cross-sections with H($\gamma\gamma$) and H(4ℓ) decays - Eur. Phys. J. C 84, 78 (2024) arXiV:2402.00426

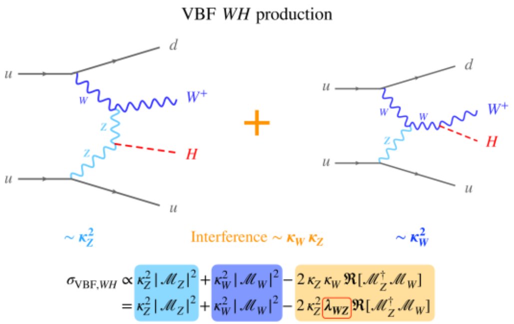
VBF WH

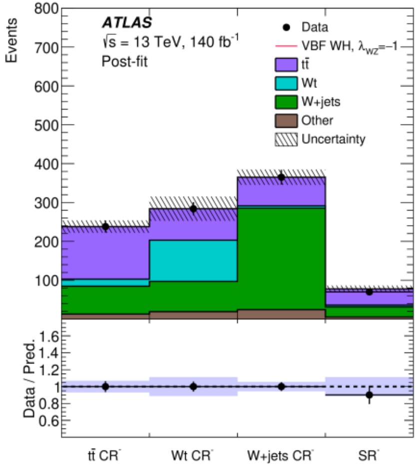
Sensitive to **ratio of Higgs couplings to W and Z**, $\lambda_{WZ} = \kappa_W/\kappa_Z$

- λ_{WZ} =1 in the SM → low cross-section
- λ_{WZ} < 0 in some BSM models → enhancement in cross-section + modified kinematics

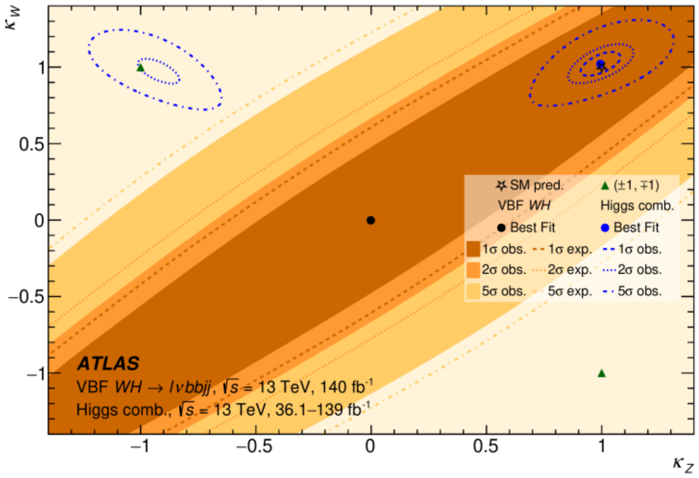
Events with one lepton, 2 b-tagged jets, ≥ 2 non b-tagged jets (2 tagged as VBF jets)

2 separate (similar) analyses for λ_{WZ} > 0 and λ_{WZ} < 0





VBF WH - results



Region of $\lambda_{WZ} = k_W/k_Z < 0$ within 2σ boundaries of latest ATLAS combination Nature 607, 52 (2022)

Excluded by $\lambda_{WZ} < 0$ analysis with significance greater than $5\sigma \Rightarrow \boldsymbol{\lambda_{WZ}} > 0$ **!**

$\lambda_{WZ} > 0$ analysis obtains for the signal strength $\mu = \sigma/\sigma_{pred.} = 0.9^{+4.0}_{-4.3}$

- upper limit of 9.0, equivalent to $\sigma \times B(H \to b\bar{b})$= 308 fb

High-pT V(qq)H(bb)

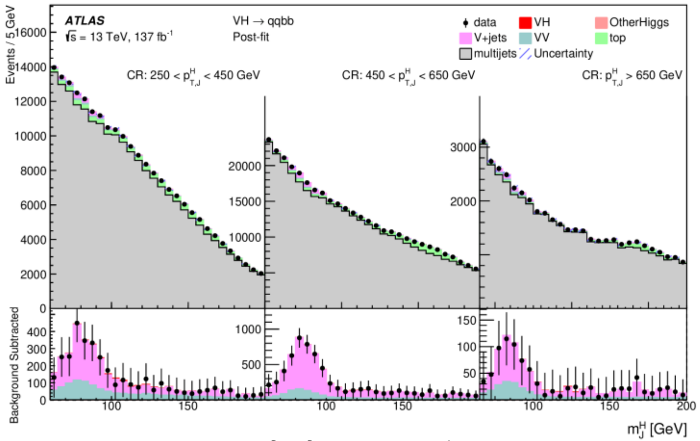
High-pT phase spaces very sensitive to new physics contributions in VH production

- V(qq)H(bb) channel has highest statistics - difficult due to **large multijet background**

Events with 2 large-R jets tagged as W/Z→ qq and H → bb

Multijet background estimated from data in CR

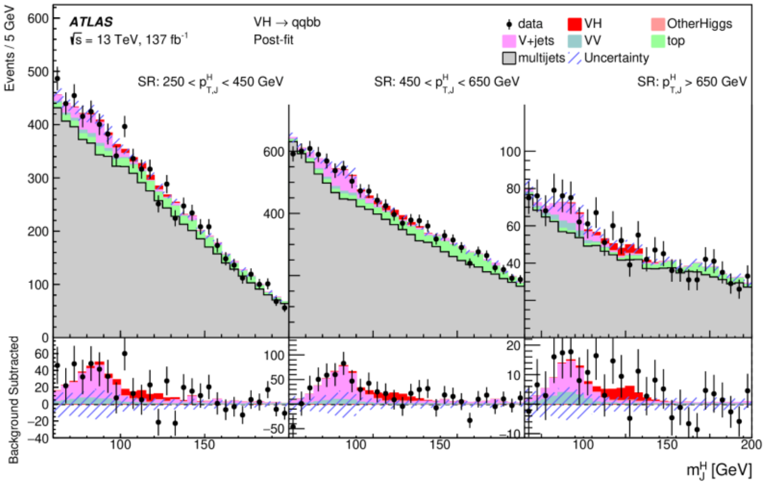
- Extrapolated to SR using **transfer factors**
- Alternative method (BDT) for validation and derivation of uncertainties



Transfer factor control region

Phys. Rev. Lett. 132, 131802 (2024)

High-pT V(qq)H(bb) - results



Fit to the invariant mass inclusive in p_T^H

- $\mu = 1.4^{+1.0}_{-0.9}$, dominated by syst. uncertainty
- Dominant systematic: multijet shape uncertainty
- Significance: 1.7σ (1.2σ) obs. (exp.)

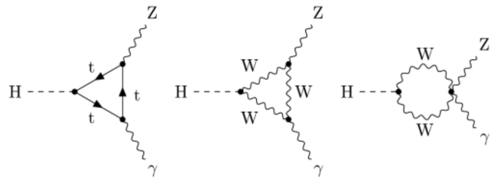
Additional fit of μ in each p_T^H category.

All results agree with SM prediction !

- Larger data samples and improved methods will improve analysis sensitivity

Phys. Rev. Lett. 132, 021803 (2024)

$Z\gamma$ decay (ATLAS+CMS)

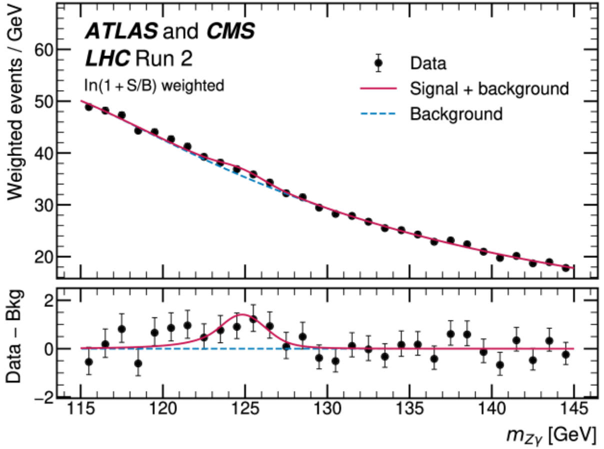


Rare (loop) decay ($B_{SM} = 1.54 \times 10^{-3}$)

- sensitive to BSM heavy particles

Events assigned to different categories, with different S/B:

- ATLAS: 6 categories, inc. 1 targetting VBF topology
- CMS: 8 categories, inc. 1 targetting VH/ttH and 3 based on BDT targetting VBF

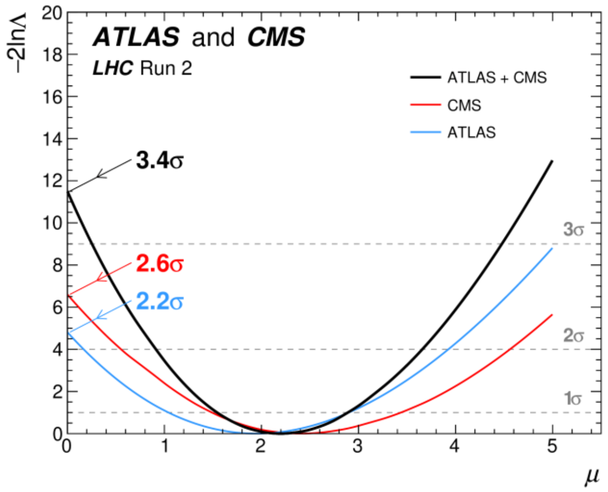


Signal and background modelled with analytical functions

- **Definition of background models** is the main difference between ATLAS and CMS analyses

Phys. Rev. Lett. 132, 021803 (2024)

$Z\gamma$ decay (ATLAS+CMS) - results



Several theoretical uncertainties correlated

$\mu = 2.2 \pm 0.7$, dominated by statistical uncertainty

- Dominant systematic: $H \to Z\gamma$ branching fraction, background modelling

Combined significance > 3σ – **first evidence @ LHC !**

Fit to branching ratio (assuming SM production cross-sections):

- $B(H \to Z\gamma) = (3.4 \pm 1.1) \times 10^{-3}$ (1.9σ away from SM) arXiV:2312.02394

V(leptons)H($\tau\tau$)

Rare production+decay mode $(\sigma \times B)_{SM} = 6.59 \pm 0.03$ fb

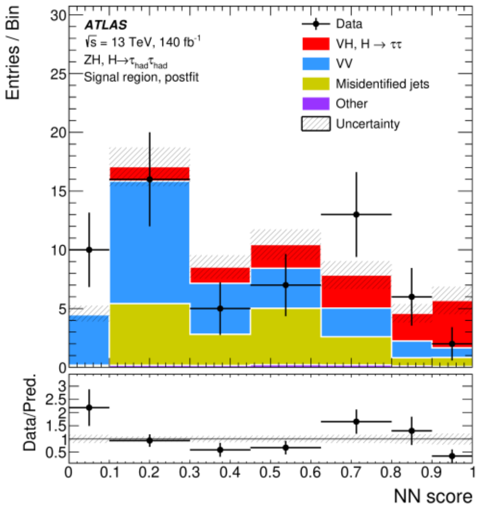
Events with light leptons and ≥ 1 hadronically decaying taus

- Improved methods for hadronic tau identification (ML-based)

Misidentified jet background estimated from data.

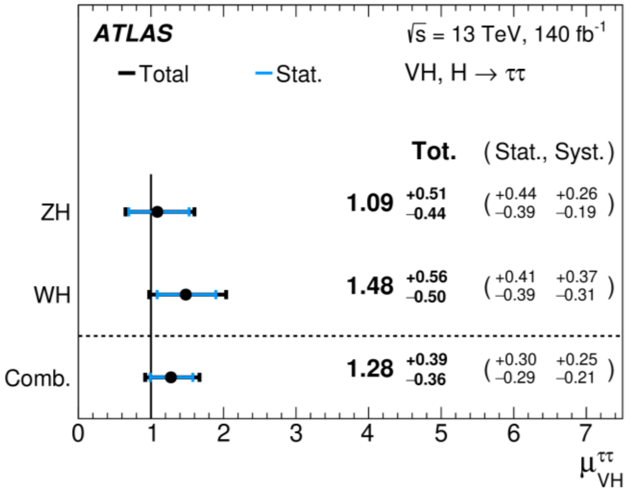
Neural network (NN) to separate signal from diboson background

- Mass-based analysis as cross check



arXiV:2312.02394

V(leptons)H($\tau\tau$) - results



Fitting combined signal strengths + split in WH/ZH

- Dominated by statistical uncertainty
- Dominant systematic: tau reconstruction

Significance: 4.2σ (3.6σ) observed (expected)

Results **consistent with the SM.**

Mass-based analysis: similar signal strengths, lower significance - 3.5σ obs., 2.6σ exp.

- Shows power of machine learning techniques

ATLAS-CONF-2024-007

NEW !

H($\tau\tau$) STXS

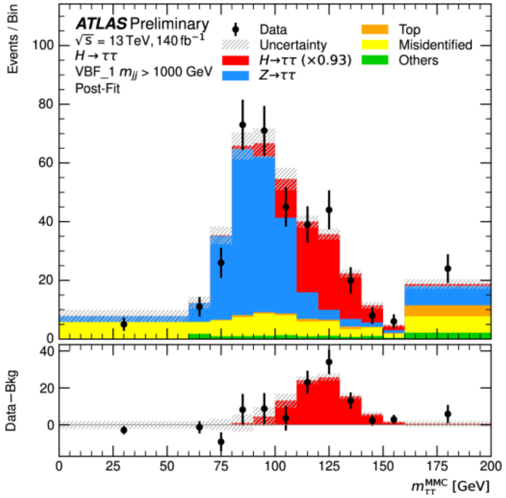
Cross-sections for specific production modes/regions of phase space:

- VBF, V(qq)H, ttH(0L)H($\tau_{had}\tau_{had}$), ggH (high-pT)
- Categorization in #jets, p_T^H and m_{jj}

New w.r.t. previous Run 2 analysis:

- Finer split in VBF and ttH
- Reconstruction of p_T^H for categorization improved with NN

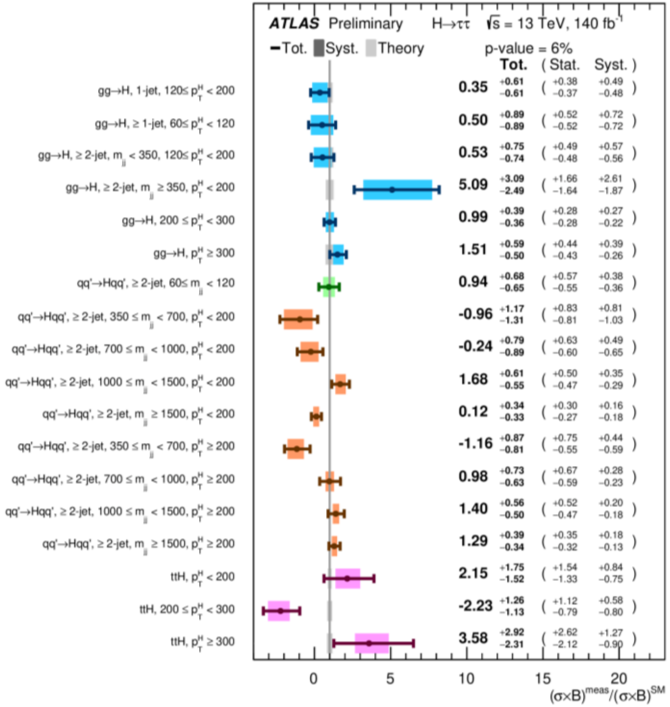
BDT discriminants to separate signal- and background-rich regions



[ATLAS-CONF-2024-007]

H($\tau\tau$) STXS - results

NEW !



Highlights:

- first VBF STXS measurement for high p_T^H
- most precise VBF STXS measurements for low p_T^H
- **25% improvement** on ttH μ w.r.t. previous publication
- 95% CL upper limits on ttH STXS

All results **consistent with the SM.**

[Eur. Phys. J. C 84, 78 (2024)]

H($\gamma\gamma$), H(4ℓ) @ 13.6 TeV

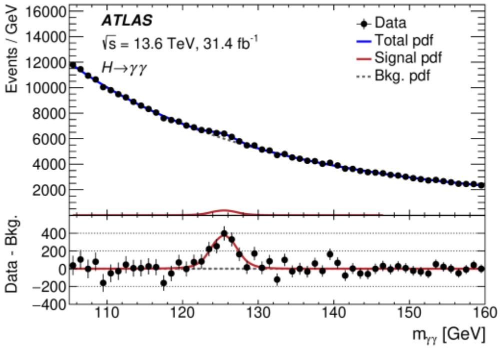
Inclusive Higgs boson production cross-section @ 13.6 TeV

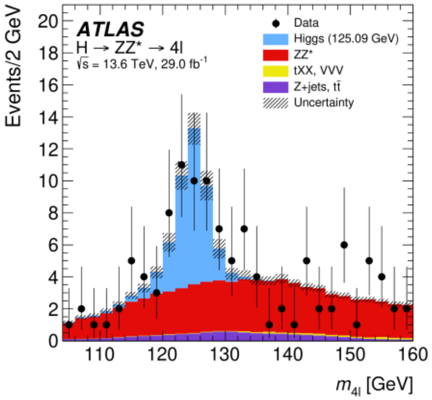
1. fiducial cross-section measurement
2. extrapolation to full phase space

New: H→ $\gamma\gamma$ uses generative ML model to create very high-statistics template of the continuum $\gamma\gamma^*$ background

- More accurate estimation of background modelling uncertainty

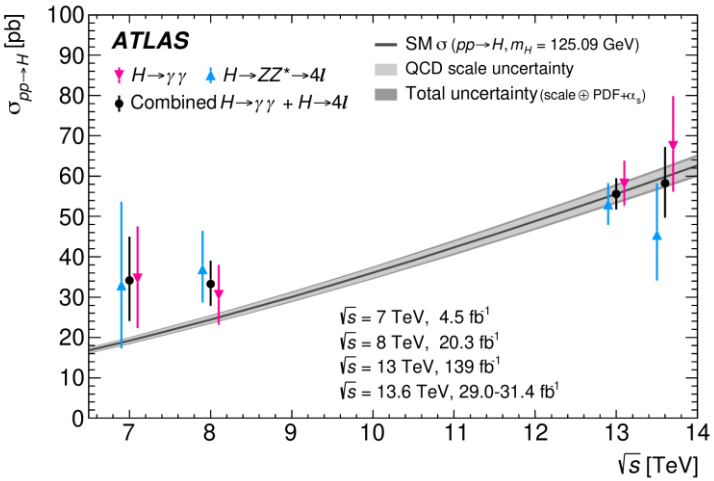
Measured-fiducial correction factors derived from simulated signal.





[Eur. Phys. J. C 84, 78 (2024)]

H($\gamma\gamma$), H(4ℓ) @ 13.6 TeV - results



Full phase space cross-sections $\sigma(pp \to H)$:

- H→ $\gamma\gamma$: 67^{+12}_{-11} pb
- H→ 4ℓ: 46 ± 12 pb
- H→ $\gamma\gamma$ + H→ 4ℓ: $58.2 \pm 7.5\,(stat.) \pm 4.5\,(syst.)$ pb

Dominant systematics:

- H→ $\gamma\gamma$: background modelling
- H→ 4ℓ: lepton reconstruction uncertainties

Measured cross-sections agree with SM value, $\sigma(pp \to H)_{SM} = 59.9 \pm 2.6$ pb

- **A lot more to come from Run 3 dataset !**

Conclusions

ATLAS continues its exploration of the Higgs boson sector:

- $\lambda_{WZ} < 0$ excluded at $> 5\sigma$, evidence of $\mathrm{H} \rightarrow Z\gamma$ (with CMS), …
- first ATLAS Higgs measurements at 13.6 TeV

Latest results agree with the SM quite well… but we're not stopping yet

- Still coming up with creative methods and analyses ideas to explore the Run 2 dataset
- Collecting more (and better) data in Run 3 dataset

Always hopeful for a sign of new physics !

Backup

VBF WH - I

Predictions were obtained for various values of κW and κZ using the procedure outlined in Phys. Rev. D **102**, 033006

Variable	Description	SR^-	$\mathrm{SR}^+_{\mathrm{loose}}$	$\mathrm{SR}^+_{\mathrm{tight}}$
$m_{b\bar{b}}$	Invariant mass of the two b-jets ($b\bar{b}$ system).	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV	$\in (105, 145)$ GeV
$\Delta R_{b\bar{b}}$	ΔR between the two b-jets.	< 1.2	< 1.6	< 1.2
$p_{\mathrm{T}}^{b\bar{b}}$	p_{T} of the $b\bar{b}$ system.	> 250 GeV	> 100 GeV	> 180 GeV
m_{jj}	Invariant mass of the VBF jets.	–	> 600 GeV	> 1000 GeV
Δy_{jj}	Rapidity separation of the VBF jets.	> 4.4	> 3.0	> 3.0
$m_{\mathrm{top}}^{\mathrm{lep}}$	Invariant mass of the W and either b-jet that is closest to 172.7 GeV.	> 260 GeV	> 260 GeV	> 260 GeV
$\xi_{Wb\bar{b}}$	$\frac{\lvert y_{Wb\bar{b}} - y_{jj}\rvert}{\Delta y_{jj}}$, where $y_{Wb\bar{b}}$ (y_{jj}) is the rapidity of the $Wb\bar{b}$ (VBF-jet) system.	< 0.3	< 0.3	< 0.3
$\Delta\phi(Wb\bar{b}, jj)$	Azimuthal separation between the $Wb\bar{b}$ system and the VBF-jet system.	–	–	> 2.7
$N_{\mathrm{jets}}^{\mathrm{veto}}$	Number of nontagged, non-VBF jets with $p_{\mathrm{T}} > 25$ GeV and $\lvert\eta\rvert < 2.5$.	–	≤ 1	$= 0$

Variable	$t\bar{t}$ CR$^-$	$t\bar{t}$ CR$^+$	W+jets CR$^-$	W+jets CR$^+$	Wt CR$^-$	Wt CR$^+$
$m_{b\bar{b}}$	> 145 GeV	> 145 GeV	< 70 GeV	< 70 GeV	> 145 GeV	> 145 GeV
$\Delta R_{b\bar{b}}$	< 1.2	< 1.2	$< 2.23 - 0.007 p_{\mathrm{T}}^{b\bar{b}}/\mathrm{GeV}$	$< 2.23 - 0.007 p_{\mathrm{T}}^{b\bar{b}}/\mathrm{GeV}$	> 1.5	> 1.6
$p_{\mathrm{T}}^{b\bar{b}}$	> 200 GeV	–	$\in (150, 250)$ GeV	> 80 GeV	> 250 GeV	> 180 GeV
$m_{\mathrm{top}}^{\mathrm{lep}}$	> 260 GeV	> 220 GeV	> 275 GeV	> 260 GeV	> 320 GeV	> 320 GeV
Δy_{jj}	$\in (3, 4.4)$	> 3	> 3	> 3	> 3	> 3
m_{jj}	–	$\in (400, 1000)$ GeV	–	> 500 GeV	–	> 500 GeV
$N_{\mathrm{jets}}^{\mathrm{veto}}$	–	< 2	–	< 1	–	< 2
p_{T}^{W}	–	< 350 GeV	–	–	> 250 GeV	> 250 GeV
m_{T}^{W}	–	–	–	< 200 GeV	–	–
p_{T}^{j1}	–	–	> 70 GeV	> 70 GeV	< 350 GeV	< 350 GeV

VBF WH - II

Uncertainty source	$\Delta\mu$
$t\bar{t}$ modelling	± 0.033
Jet energy resolution	± 0.017
Wt modelling	± 0.013
Jet energy scale	± 0.011
Signal modelling	± 0.007
W+jets modelling	± 0.006
MC statistical uncertainty	± 0.005
Jet vertex tagging	± 0.003
Flavor tagging	± 0.002
E_T^{miss} scale and trigger efficiency	± 0.001
Luminosity and pileup reweighting	± 0.001
Other background modelling	± 0.001
Lepton scale and efficiency	< 0.001
Total systematic	± 0.045
Normalization factors	± 0.016
Total statistical	± 0.032
Total uncertainty	± 0.055

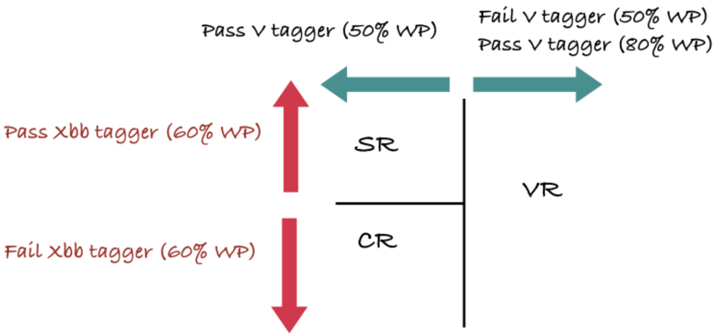
$\lambda_{WZ} < 0$

Uncertainty source	$\Delta\mu$
W+jets modelling	± 1.9
$t\bar{t}$ modelling	± 1.8
Jet energy resolution	± 1.3
Jet energy scale	± 0.8
MC statistical uncertainty	± 0.8
Other background modelling	± 0.5
Signal modelling	± 0.4
Wt modelling	± 0.3
E_T^{miss} scale and trigger efficiency	± 0.3
Flavor tagging	± 0.1
Luminosity and pileup reweighting	± 0.1
Jet vertex tagging	± 0.1
Lepton scale and efficiency	< 0.1
Total systematic	± 3.3
Normalization factors	± 1.4
Total statistical	± 2.5
Total uncertainty	± 4.1

$\lambda_{WZ} > 0$

High-pT V(qq)H(bb) - I

Kinematic region	Observed μ	Observed σ [fb]	Expected σ [fb]
$250 \leq p_{\mathrm{T}}^{H} < 450$ GeV, $\lvert y_H \rvert < 2$	$0.8^{+2.2}_{-1.9}$	47^{+125}_{-109}	57.0
$450 \leq p_{\mathrm{T}}^{H} < 650$ GeV, $\lvert y_H \rvert < 2$	$0.4^{+1.7}_{-1.5}$	2^{+10}_{-9}	5.9
$p_{\mathrm{T}}^{H} \geq 650$ GeV, $\lvert y_H \rvert < 2$	$5.3^{+11.3}_{-3.2}$	6^{+13}_{-4} (<43)	1.2



Uncertainty source	$\delta\mu$
Signal modeling	$^{+0.10}_{-0.02}$
MC statistical uncertainty	$^{+0.13}_{-0.13}$
Instrumental (pileup, luminosity)	$^{+0.012}_{-0.004}$
Large-R jet	$^{+0.13}_{-0.14}$
Top-quark modeling	$^{+0.14}_{-0.15}$
Other theory modeling	$^{+0.05}_{-0.03}$
$H \to b\bar{b}$ tagging	$^{+0.52}_{-0.23}$
Multijet estimate (TF uncertainty)	$^{+0.52}_{-0.41}$
Multijet modeling (TF vs. BDT)	$^{+0.14}_{-0.18}$
Total systematic uncertainty	$^{+0.80}_{-0.61}$
Signal statistical uncertainty	$^{+0.60}_{-0.60}$
Z+jets normalization	$^{+0.42}_{-0.20}$
Total statistical uncertainty	$^{+0.63}_{-0.63}$
Total uncertainty	$^{+1.02}_{-0.88}$

V(leptons)H($\tau\tau$) - I

Category	Region	Cuts	Major process contributing to the background from misidentified jets
$WH,\ H \to \tau_{had}\tau_{had}$	W+jets	PRESELECTION same-sign $\tau_{had\text{-}vis}$ $m_T(\ell, E_T^{miss}) < 60$ GeV	W+jets ~ 70%
	$Z \to \tau\tau$	PRESELECTION $m_{2T} < 60$ GeV $m_T(\ell, E_T^{miss}) < 40$ GeV	$Z \to \tau\tau$ ~ 50%
	top-quark	PRESELECTION # b jets > 0	$t\bar{t}$ ~ 70%
$WH,\ H \to \tau_{lep}\tau_{had}$	$Z \to \tau\tau$	PRESELECTION opposite-sign light leptons $m_{coll}(\ell,\ell) \in [60, 120]$ GeV $m_{ee} \notin [80, 100]$ GeV	$Z \to \tau\tau$ ~ 40%
	All Same Sign	PRESELECTION all objects with same-sign $m_{ee} \notin [80, 100]$ GeV	W+jets ~ 70%

Selection	$WH,\ H \to \tau_{lep}\tau_{had}$	$WH,\ H \to \tau_{had}\tau_{had}$	$ZH,\ H \to \tau_{lep}\tau_{had}$	$ZH,\ H \to \tau_{had}\tau_{had}$
PRESELECTION	exactly 1 $\tau_{had\text{-}vis}$ exactly 2 ℓ b-jet veto	exactly 2 $\tau_{had\text{-}vis}$ exactly 1 ℓ b-jet veto	exactly 1 $\tau_{had\text{-}vis}$ exactly 3 ℓ same-flavour, OS ℓ pair $m_{\ell\ell} \in [81, 101]$ GeV	exactly 2 $\tau_{had\text{-}vis}$ exactly 2 ℓ same-flavour, OS ℓ pair $m_{\ell\ell} \in [71, 111]$ GeV
SIGNAL REGION	1 $\tau_{had\text{-}vis}$ and 1 τ_{lep} OS exactly 2 ℓ SS $\sum_\ell p_T(\ell) + p_T(\tau_{had\text{-}vis}) > 90$ GeV $m_{ee} \notin [80, 100]$ GeV	exactly 2 $\tau_{had\text{-}vis}$ OS $0.8 < \Delta R(\tau_{had\text{-}vis}, \tau_{had\text{-}vis}) < 2.8$ $\sum_{\tau_{had\text{-}vis}} p_T(\tau_{had\text{-}vis}) > 100$ GeV $m_T(\ell, E_T^{miss}) > 20$ GeV	exactly 1 $\tau_{had\text{-}vis}$ and 1 τ_{lep} OS $\sum_{\tau_{had\text{-}vis}, \tau_{lep}} p_T(\tau) > 60$ GeV	exactly 2 $\tau_{had\text{-}vis}$ OS $\sum_{\tau_{had\text{-}vis}} p_T(\tau) > 75$ GeV
HIGGS BOSON MASS WINDOW CUT (ONLY APPLIED IN THE NN-BASED ANALYSIS)	$m_{2T} \in [60, 130]$ GeV	$m_{2T} \in [80, 130]$ GeV	$m_{MMC} \in [100, 170]$ GeV	$m_{MMC} \in [100, 180]$ GeV

V(leptons)H($\tau\tau$) - II

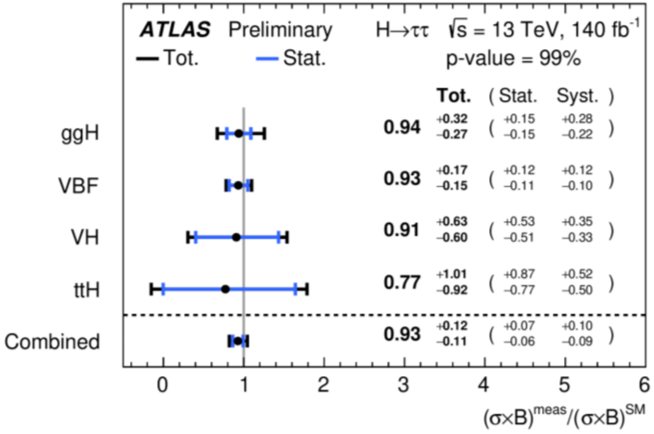
All categories	$ZH,\ H \to \tau_{had}\tau_{had}$	$ZH,\ H \to \tau_{lep}\tau_{had}$	$WH,\ H \to \tau_{had}\tau_{had}$
N-prongs(τ_1)	N-prongs(τ_2)	$p_T(\ell_2)$	N-prongs(τ_2)
$p_T(\tau_1)$	$p_T(\tau_2)$	$\eta(\ell_2)$	$p_T(\tau_2)$
$\eta(\tau_1)$	$\eta(\tau_2)$	$\phi(\ell_2)$	$\eta(\tau_2)$
$\phi(\tau_1)$	$\phi(\tau_2)$	$p_T(H)$	$\phi(\tau_2)$
$\Delta R(\tau_1, \ell_1)$	$p_T(\ell_2)$	$\eta(\ell_\tau)$	$\sqrt{\eta(\ell_1)^2 + \phi(\ell_1)^2}$
$p_T(l_1)$	$\eta(\ell_2)$	$\phi(\ell_\tau)$	
$\eta(\ell_1)$	$\phi(\ell_2)$	$\Delta R(\ell, \ell)$	
$\phi(\ell_1)$	$m_{\ell\ell}$	$m_{\ell\ell}$	
$p_T(E_T^{miss})$	$\Delta R(\ell, \ell)$		
$\phi(E_T^{miss})$			
	$WH,\ W \to e\nu_e,\ H \to \tau_e\tau_{had}$	$WH,\ W \to e(\mu)\nu_{e(\mu)},\ H \to \tau_{\mu(e)}\tau_{had}$	$WH,\ W \to \mu\nu_\mu,\ H \to \tau_\mu\tau_{had}$
	$p_T(\ell_\tau)$	$p_T(\ell_\tau)$	$p_T(\ell_\tau)$
	$\eta(\ell_\tau)$	$\eta(\ell_\tau)$	$\eta(\ell_\tau)$
	$\phi(\ell_\tau)$	$\phi(\ell_\tau)$	$\phi(\ell_\tau)$
	$\Delta\eta(\ell, \ell_\tau)$	$\Delta\eta(\ell, \ell_\tau)$	$\Delta\eta(\ell, \ell_\tau)$
	jet width(τ_1)	jet width(τ_1)	jet width(τ_1)
	$p_T(H)$	$m(\tau_1, \ell_\tau)$	$\Delta R(\ell, \ell_\tau)$
	$m(\tau_1, \ell_\tau)$	$\Delta R(\ell, \ell_\tau)$	$m(\tau_1, l_\tau)$
	$\Delta\eta(\tau_1, \ell_\tau)$	$\Delta\eta(\tau_1, \ell_\tau)$	$\Delta\eta(\tau_1, \ell_\tau)$
	$\Delta\phi(l_1, \ell_\tau)$	$\sum p_T$(all visible)	$\Delta R(\tau_1, \ell_\tau)$
	$\Delta_\phi(\tau_1,\ E_T^{miss})$	$\Delta\phi(\tau_1, E_T^{miss})$	$\sum p_T$(all visible)
	$\Delta R(\ell, \ell_\tau)$		$\Delta\phi(\ell_1, \ell_\tau)$

NN variables

Source of uncertainty	$\delta\mu/\mu_{VH}^{\tau\tau}$ [%]
Hadronic τ–lepton decay	9
Simulated background sample size	9
Misidentified jets	4
Jet and E_T^{miss}	4
Theoretical uncertainty in signal	4
Theoretical uncertainty in top-quark, VV and VVV processes	4
Electrons and muons	2
Luminosity	1
Flavour tagging	< 1
Total systematic uncertainty	16
Total statistical uncertainty	24
Total	30

Uncertainty breakdown

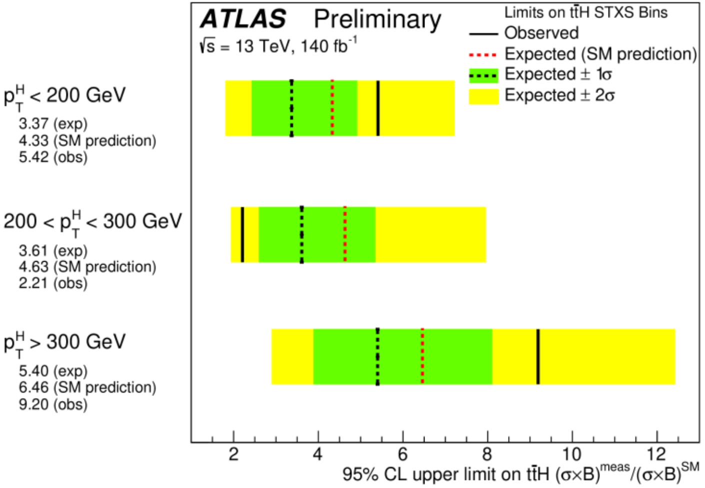
$H(\tau\tau)$ STXS

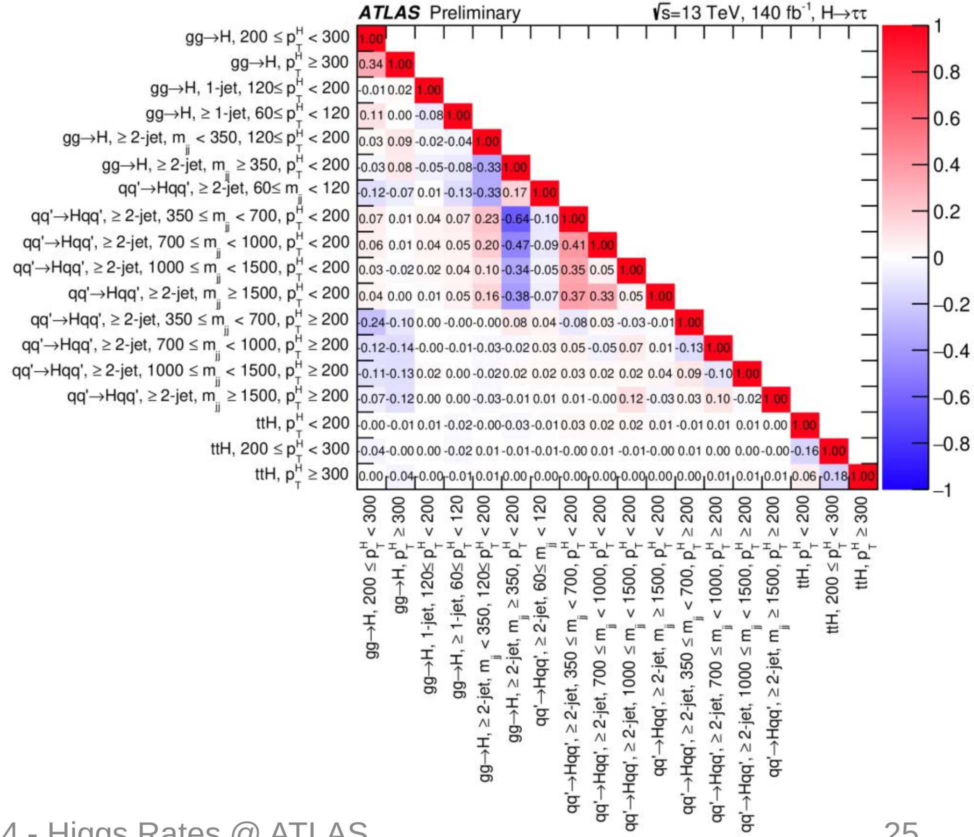


	Variable	VBF	ttH multiclass
Jet properties	Invariant mass of the two leading jets	•	
	$p_T(jj)$	•	
	Product of η of the two leading jets	•	
	Sub-leading jet p_T	•	
	η of the 5 leading jets		•
	Scalar sum of all jets p_T		•
	Scalar sum of all b-tagged jets p_T		•
	Best W-candidate dijet invariant mass		•
	Best t-quark-candidate three-jet invariant mass		•
Angular distances	$\Delta\phi$ between the two leading jets	•	
	$\Delta\eta$ between the two leading jets	•	
	Minimum ΔR between two jets		•
	Minimum ΔR between a b-tagged jet and a $\tau_{\text{had-vis}}$		•
	$\lvert\Delta\eta(\tau,\tau)\rvert$		•
	$\Delta R(\tau,\tau)$		•
τ prop.	$p_T(\tau\tau)$		•
	Sub-leading τ p_T		•
	Leading τ η		•
H cand. plus jets system	$p_T(Hjj)$	•	
$\vec{E}_T^{\text{miss}}$	Missing transverse momentum E_T^{miss}		•
	Smallest $\Delta\phi$ $(\tau, \vec{E}_T^{\text{miss}})$		•

VBF inclusive	sub-leading jet $p_T > 30$ GeV $m_{jj} > 350$ GeV, $\lvert\Delta\eta_{jj}\rvert > 3$ $\eta(j_0) \times \eta(j_1) < 0$ lepton centrality: visible decay products of the τ leptons between VBF jets
VH inclusive	60 GeV $< m_{jj} <$ 120 GeV sub-leading jet $p_T > 30$ GeV
$\mathbf{tt(0\ell)H \to \tau_{had}\tau_{had}}$	# of jets ≥ 6 and # of b-jets ≥ 1 or # of jets ≥ 5 and # of b-jets ≥ 2
Boost inclusive	Not VBF inclusive Not VH inclusive $p_T(H) > 100$ GeV

H($\tau\tau$) STXS - II





$H(\gamma\gamma)$

Photons	
Leading (sub-leading) p_T^{γ}	$p_T^{\gamma}/m_{\gamma\gamma} > 0.35(0.25)$
Pseudorapidity	$\lvert\eta\rvert < 2.47$ and outside $1.37 < \lvert\eta\rvert < 1.52$
Isolation	$E_T^{iso}/E_T^{\gamma} < 0.05$
Di-photon system	
Mass window	$105\ \text{GeV} < m_{\gamma\gamma} < 160\ \text{GeV}$

Fiducial selection

Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.4

Uncertainty breakdown

$H(4\ell)$

Source	Uncertainty [%]
Statistical uncertainty	25.1
Systematic uncertainty	7.9
Electron uncertainties	6.3
Muon uncertainties	3.8
Luminosity	2.2
ZZ^* theoretical uncertainties	0.7
Reducible background estimation	0.6
Other uncertainties	<1.0
Total	26.4

Uncertainty breakdown

Leptons	
Muons	$p_T > 5$ GeV, $\|\eta\| < 2.5$
Electrons	$E_T > 7$ GeV, $\|\eta\| < 2.47$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one Higgs boson candidate per channel)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and $m_{\text{threshold}} < m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Impact parameter	$\|d_0\|/\sigma(d_0)$ <5 (3) for electrons (muons)
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
Vertex selection	$\chi^2/N_{\text{dof}} < 6$ (9) for 4μ (other channels)
If extra lepton with $p_T > 12$ GeV	quadruplet with largest ME value

Detector-level selection

Leptons	
Leptons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	quadruplet with largest matrix element value

Fiducial selection