Searches with H$\rightarrow \tau\tau$ at ATLAS

Antonio De Maria
on the behalf of the ATLAS collaboration

Higgs2023

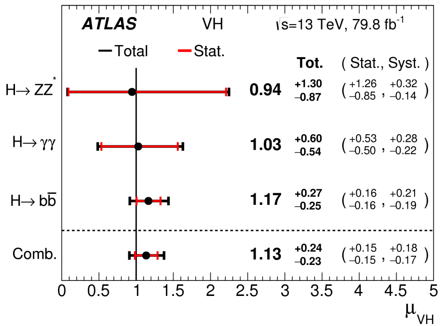
Introduction

- Next slides are going to describe two new analyses recently published by the ATLAS experiment considering the $H \to \tau\tau$ decay:
  - *Evidence of the $VH, H \to \tau\tau$ process with the ATLAS detector in Run 2*
  - *Search for the non-resonant production of Higgs boson pairs via gluon fusion and vector-boson fusion in the $b\bar{b}\tau^{+}\tau^{-}$ final state in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector* Reference
- Results from both analyses are presented for the first time in a conference
- Results will be also discussed in the following talks:
  - *"Measurements of third generation Higgs boson Yukawa couplings"* by C. Palmer
  - *"Di-Higgs searches, status and future prospects: non-resonant"* by M. Valente
  - *"Probing the nature of electroweak symmetry breaking with Higgs boson pair-production at ATLAS"* by T.J. Khoo
  - *"Constraining the Shape of the Higgs Potential Through a Search for Higgs Boson Pairs in the bbtautau Final State with the ATLAS Experiment"* by B. Moser

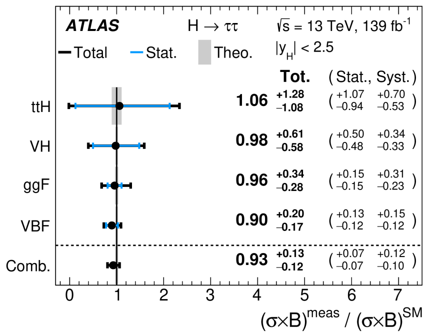
Introduction to $VH, H \to \tau\tau$ analysis

- Higgs boson associated production with a vector boson (VH) is one of the four main Higgs boson production modes at LHC
- $H \to \tau\tau$ decay important for Higgs to fermion Yukawa coupling measurement
- Both processes have been already observed separately:
  - VH measured with an observed (expected) significance of 5.3 (4.8) σ from early Run2 combination of $H \to ZZ^*$, $H \to \gamma\gamma$ and $H \to b\bar{b}$ decays
  - $H \to \tau\tau$ cross-section measurement per production mode focused only on associated production with V decaying hadronically

VH observation



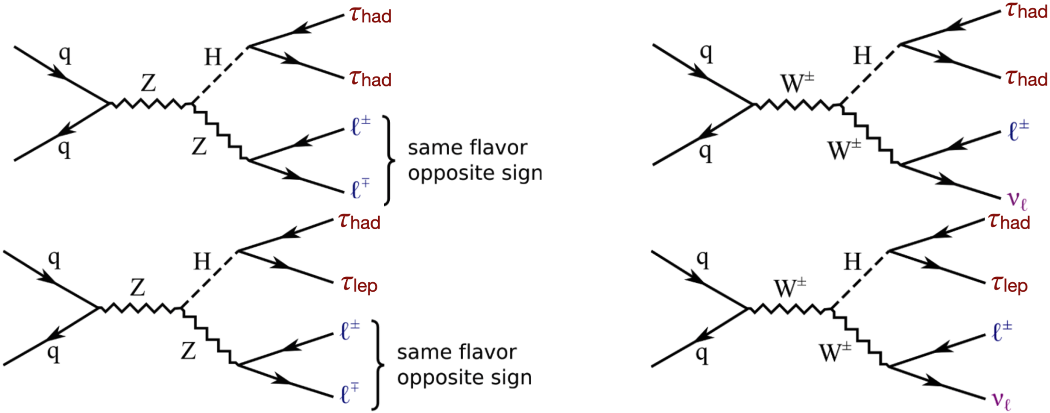
H→ $\tau\tau$ Coupling



- $VH, H \to \tau\tau$ process with V decaying leptonically still not observed
  - Previous analysis with Run1 dataset only able to set cross-section upper limit VH-R1

Cross-section measurement of VH, $H \to \tau\tau$ with V decaying leptonically

- Considering final states with at least one τ decaying hadronically ($\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$) and the V decaying leptonically ($W \to l\nu$, $Z \to ll$ with $l = e, \mu$)
  - For $WH(\tau_{lep}\tau_{had})$, final states with two electrons/muons also included, unlike previous Run1 analysis
- Final states with both τ decaying leptonically not considered to preserve orthogonality with $H \to WW^*$ analyses



Event selection and analysis workflow

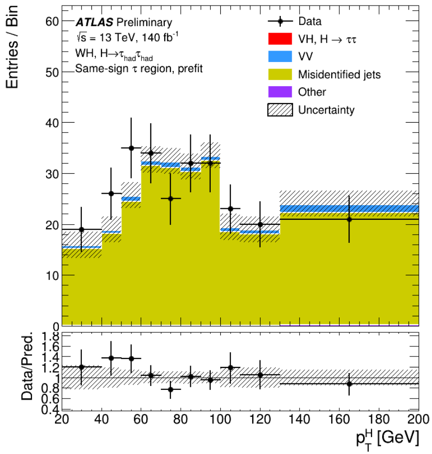
- Event selection divided into two main region types:
  - *Preselection*: used as baseline selection to define validation regions for the background modelling
  - *Signal Region*: impose additional criteria on top of the Preselection to enhance the signal over background ratio

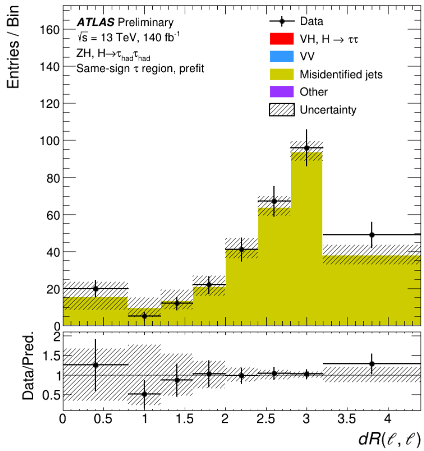
Selection	$WH,\ H \to \tau_{\text{lep}}\tau_{\text{had}}$	$WH,\ H \to \tau_{\text{had}}\tau_{\text{had}}$	$ZH,\ H \to \tau_{\text{lep}}\tau_{\text{had}}$	$ZH,\ H \to \tau_{\text{had}}\tau_{\text{had}}$
Preselection	exactly 1 $\tau_{\text{had-vis}}$ exactly 2 ℓ b-jet veto	exactly 2 $\tau_{\text{had-vis}}$ exactly 1 ℓ b-jet veto	exactly 1 $\tau_{\text{had-vis}}$ exactly 3 ℓ same-flavour, OS ℓ pair $m_{\ell\ell} \in [81, 101]$ GeV	exactly 2 $\tau_{\text{had-vis}}$ exactly 2 ℓ same-flavour, OS ℓ pair $m_{\ell\ell} \in [71, 111]$ GeV
Signal Region	1 $\tau_{\text{had-vis}}$ and 1 τ_{lep} OS exactly 2 ℓ SS $\sum_{\ell} p_{\text{T}}(\ell) + p_{\text{T}}(\tau_{\text{had-vis}}) > 90$ GeV $m_{ee} \notin [80, 100]$ GeV	exactly 2 $\tau_{\text{had-vis}}$ OS $0.8 < \Delta R(\tau_{\text{had-vis}}, \tau_{\text{had-vis}}) < 2.8$ $\sum_{\tau_{\text{had-vis}}} p_{\text{T}}(\tau_{\text{had-vis}}) > 100$ GeV $m_T(\ell, E_T^{\text{miss}}) > 20$ GeV	exactly 1 $\tau_{\text{had-vis}}$ and 1 τ_{lep} OS $\sum_{\tau_{\text{had-vis}}, \tau_{\text{lep}}} p_{\text{T}}(\tau) > 60$ GeV	exactly 2 $\tau_{\text{had-vis}}$ OS $\sum_{\tau_{\text{had-vis}}} p_{\text{T}}(\tau) > 75$ GeV
Higgs boson mass window cut (only applied in the NN-based analysis)	$m_{2\text{T}} \in [60, 130]$ GeV	$m_{2\text{T}} \in [80, 130]$ GeV	$m_{\text{MMC}} \in [100, 170]$ GeV	$m_{\text{MMC}} \in [100, 180]$ GeV

- Main analysis results extracted from a fit over a Neural Network (NN) score in the Signal Regions + mass window cut around the Higgs boson mass value
  - Cut-based analysis also performed doing a fit of the di-τ mass observable in the Signal Regions, similar to Run1 analysis

Background estimation and validation

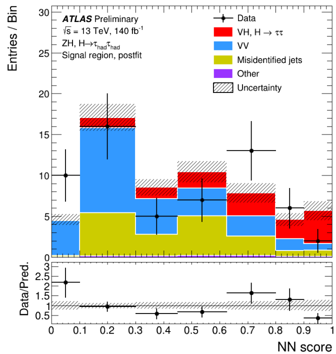
- Major background sources are VV (irreducible) and Z+jets (reducible) processes, the latter having a jet which can be mis-identified as a light lepton or τ_{had}
- Contribution from VV events estimated through simulated samples
- Contribution from events with mis-identified objects (*Fake*) is estimated using the *Fake Factor* method, considering also events with multiple mis-identified objects
- Background modelling is evaluated in several regions and additional uncertainties are assigned based on the residual modelling mismatch between data and Fake prediction

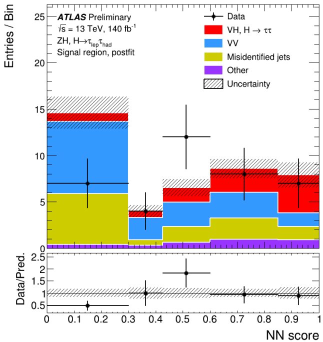


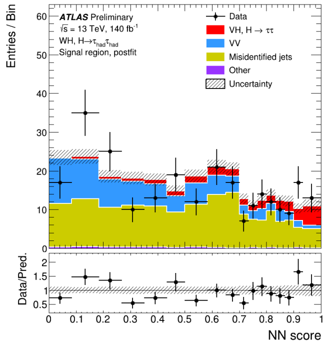


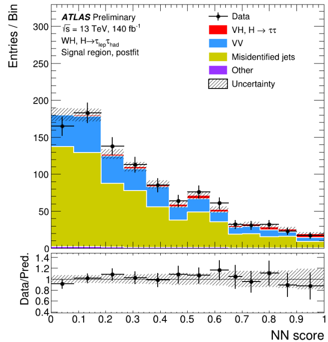
Neural Network training

- NNs trained separately for each final state; training done to distinguish signal from *VV* background using a combination of particle and event level variables



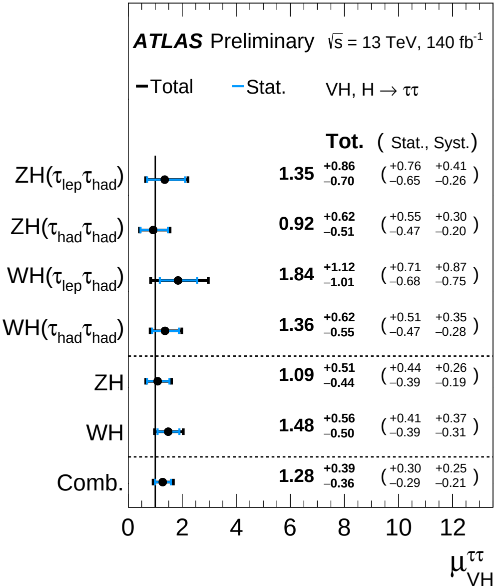


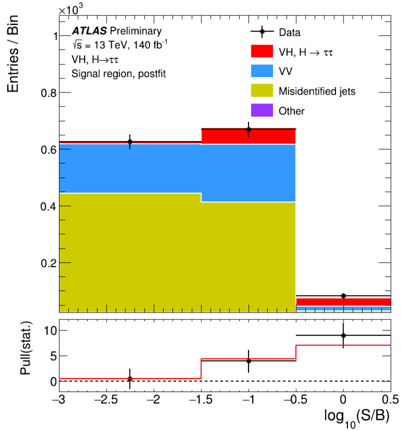




Neural Network analysis fit results

- Results extracted from a simultaneous fit of the NN score in all final states
- Observed (expected) significance of 4.2 (3.6) σ: evidence of $VH, H \to \tau\tau$ process
- Measured cross section $8.5^{+2.6}_{-2.4}$ fb, with respect to SM prediction 6.59 ± 0.03 fb





Significance (σ)	exp	obs
WH	2.2	3.3
ZH	2.9	2.8
Combined	3.6	4.2

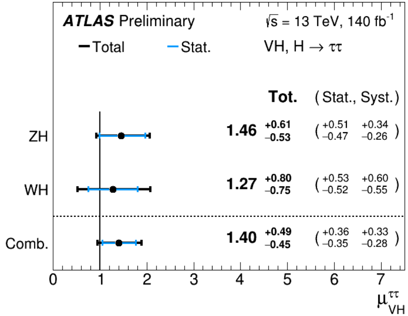
Uncertainty breakdown impact

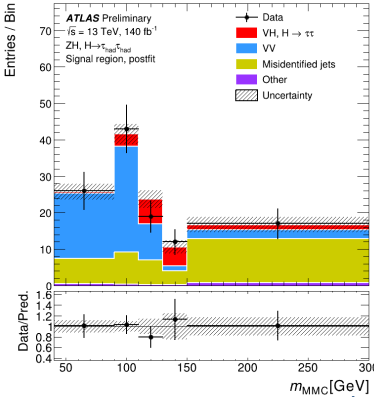
Source of uncertainty	$\delta\mu/\mu_{\mathrm{VH}}^{\tau\tau}$ [%]
Hadronic τ–lepton decay	9
Simulated background sample size	9
Misidentified jets	5
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	4
Theoretical uncertainty in signal	4
Theoretical uncertainty in top-quark, VV and VVV processes	4
Electrons and muons	2
Luminosity	1
Flavour tagging	< 1
Total systematic uncertainty	16
Total statistical uncertainty	23
Total	30

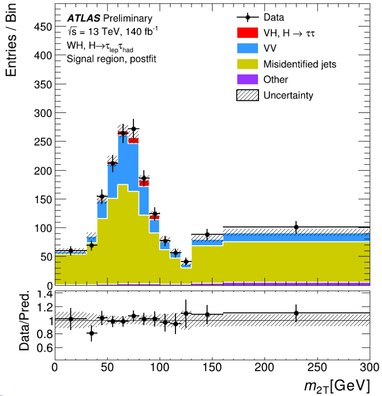
- Largest impact from data statistical uncertainty
  - Benefit from adding Run3 data to the current full Run2 dataset
- Among the systematic uncertainties, major impact from τ_{had} related uncertainties and limited statistics from simulated background samples
- Sizeable contribution also from Jet/E_T^{miss}, mis-identified objects and signal theory uncertainties

Cut-based analysis results

- Perform likelihood fit on di-τ mass observable; poor mass resolution expected due to the neutrinos in the final state
- Observed (expected) significance of 3.5 (2.5) σ. Less stringent results compared to NN fit because of lower signal/background separation power, especially for *WH* final state





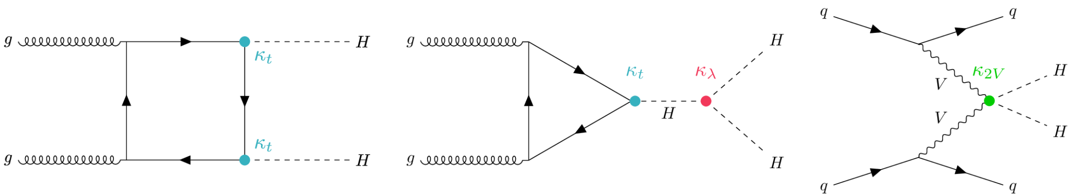


Summary of $VH, H \to \tau\tau$ analysis

- Evidence of $VH, H \to \tau\tau$ process reached with an observed (expected) significance of 4.2 (3.6) σ
- Two different analyses have been performed:
  - A Neural Network analysis; networks have been trained to separate signal from VV background using both particle and event level variables. Provides best analysis sensitivity
  - A Cut-based analysis considering the di-τ mass observable as in Run1 analysis. Provide a useful cross-check of the Neural Network analysis, though less stringent because of the lower signal/background separation power
- Largest impact on the uncertainty coming from data statistical component

Di-Higgs production

- Higgs potential influenced by Higgs boson trilinear self coupling term λ_{HHH}
- Direct way to measure the coupling is through Higgs boson pair production
- Much smaller cross-section compared to single Higgs boson production ($\simeq 10^{-3}$)
- Production mainly through gluon fusion (ggF) and vector boson fusion (VBF)
  - ggF provides most of the sensitivity to Higgs boson self-coupling modifier (κ_λ)
  - VBF provides a unique way to probe VVHH vertex (κ_{2V})



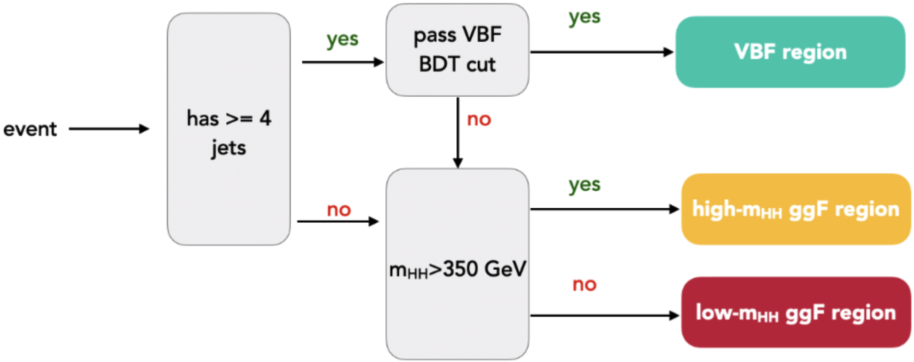
Higgs Decay	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.07%	
γγ	0.26%	0.10%	0.03%	0.01%	<0.001%

$HH \to bb\tau\tau$ Event selection

$\tau_{had}\tau_{had}$ category		$\tau_{lep}\tau_{had}$ categories	
STT	DTT	SLT	LTT
e/μ selection			
No loose e/μ		Exactly one loose e/μ	
		e (μ) must be tight (medium and have $\lvert\eta\rvert < 2.5$)	
		$p_T^e > 25, 27$ GeV	18 GeV $< p_T^e <$ SLT cut
		$p_T^\mu > 21, 27$ GeV	15 GeV $< p_T^\mu <$ SLT cut
$\tau_{had\text{-}vis}$ selection			
Two loose $\tau_{had\text{-}vis}$		One loose $\tau_{had\text{-}vis}$	
		$\lvert\eta\rvert < 2.3$	
$p_T >$ 100, 140, 180 (25) GeV	$p_T >$ 40 (30) GeV		$p_T >$ 30 GeV
Jet selection			
≥ 2 jets with $\lvert\eta\rvert < 2.5$			
Leading jet $p_T >$ 45 GeV	Trigger dependent	Leading jet $p_T >$ 45 GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{MMC} >$ 60 GeV			
Opposite-sign electric charges of $e/\mu/\tau_{had\text{-}vis}$ and $\tau_{had\text{-}vis}$			
Exactly two b-tagged jets			
		$m_{bb} <$ 150 GeV	

- Object definition/analysis main categorisation from previous publication Reference
- Considering three channels including:
  - $\tau_{lep}\tau_{had}$ events selected using Single Lepton Trigger (SLT)
  - $\tau_{lep}\tau_{had}$ events selected using Lepton+Tau Trigger (LTT)
  - $\tau_{had}\tau_{had}$ events selected using Single+DiTau Triggers

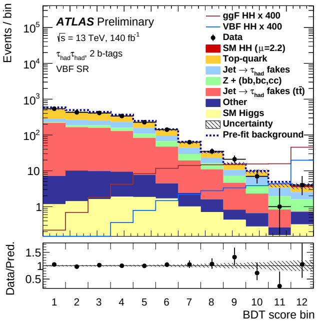
Signal Region categorisation

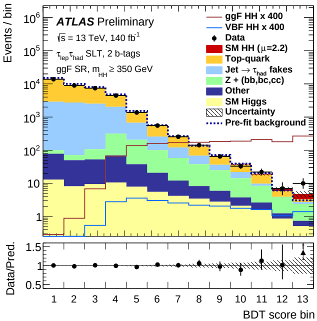


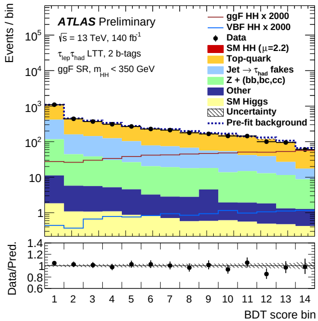
- Finer event categorisation with respect to the previous analysis
- Use Boosted Decision Trees (BDT) to select events with characteristic features of the VBF production
- Events not falling in the VBF signal region are split in two regions of m_{HH}:
  - ggF high-m_{HH}: targeting ggF production with k_λ values close to SM
  - ggF low-m_{HH}: targeting ggF production with k_λ values largely different from SM

Signal extraction though likelihood fit

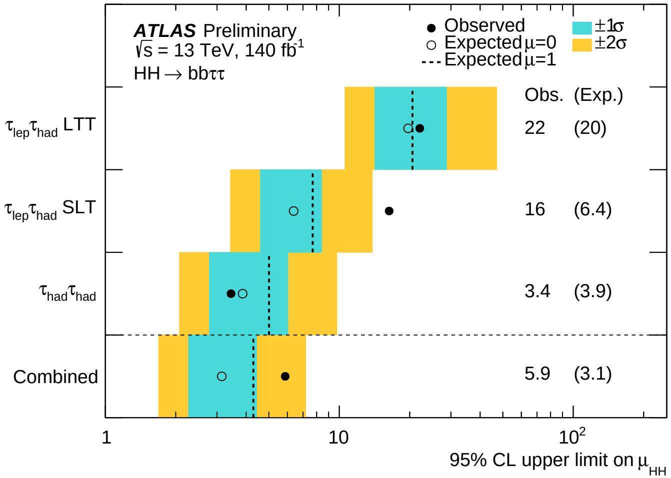
- Additional BDTs are trained in each signal region to discriminate signal against background
  - In total nine BDTs considering $\tau_{lep}\tau_{had}$ SLT/$\tau_{lep}\tau_{had}$ LTT/$\tau_{had}\tau_{had}$ regions times VBF/ggF high-m_{HH}/ggF low-m_{HH} signal regions
- BDT scores are then fit simultaneously to extract the coupling strength parameters
- Fit also includes m_{ll} distribution from a control region to constrain the normalisation of the Z+heavy flavour background







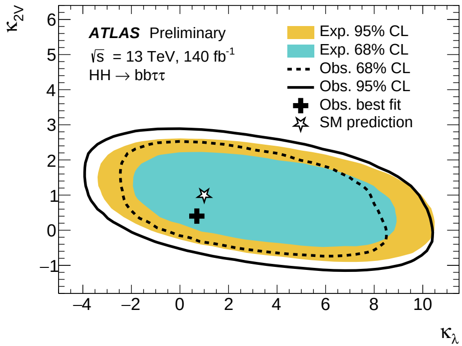
95% upper limit results on the signal strength

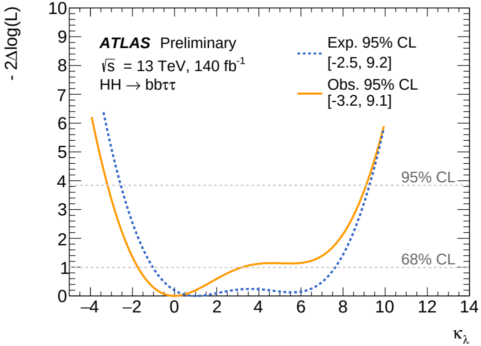


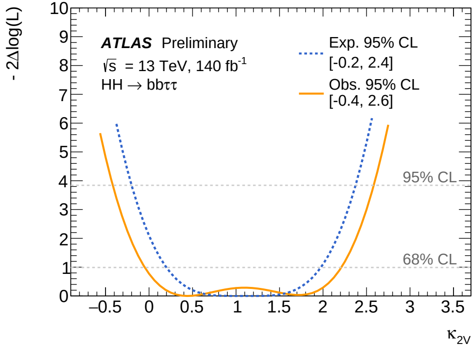
- Observed limit on μ_{HH} from the combined fit is less stringent than the expected one as a result of an excess in $\tau_{lep}\tau_{had}$ SLT SR
- Local significance of this excess is 2.3 σ with respect to SM hypothesis considering $\tau_{lep}\tau_{had}$ SLT SR standalone fit
- Expected sensitivity to μ_{HH} improved by 20% with respect to the previous results
- Sensitivity still primarily limited by the statistical uncertainty on the data

Coupling modifiers results

- Combined fit allows to set observed (expected) 95% confidence intervals for:
  - $\kappa_\lambda \in$ [-3.2, 9.1] ([-2.5, 9.2]) (assuming $\kappa_{2V} = 1$)
  - $\kappa_{2V} \in$ [-0.4, 2.6] ([-0.2, 2.4]) (assuming $\kappa_\lambda = 1$)
- Expected sensitivity improved by 10% (19%) for κ_λ (κ_{2V}) with respect to the previous results

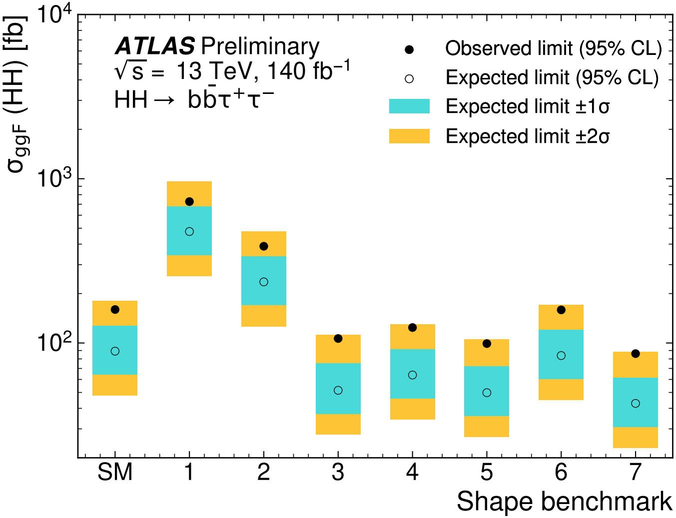






EFT Interpretation

- Cross-section limits are placed on seven HEFT shape benchmarks (Reference), built to represent different features of m_{HH} distributions
- VBF HH contribution on the m_{HH} shape benchmark limits expected to be negligible, so ignored



Summary of the $HH \to bb\tau\tau$ analysis

- An updated search for $HH \to bb\tau\tau$ analysis has been presented
- Object definition/Analysis main categorisation inherited from previous paper; considering now improved event categorisation and multivariate analysis strategy.
- With respect to previous analysis:
  - Expected sensitivity to μ_{HH} is improved by 20%
  - Expected sensitivity improved by 10% (19%) for κ_{λ} (κ_{2V})
- Sensitivity still primarily limited by the statistical uncertainty on the data

Thanks For Your Attention

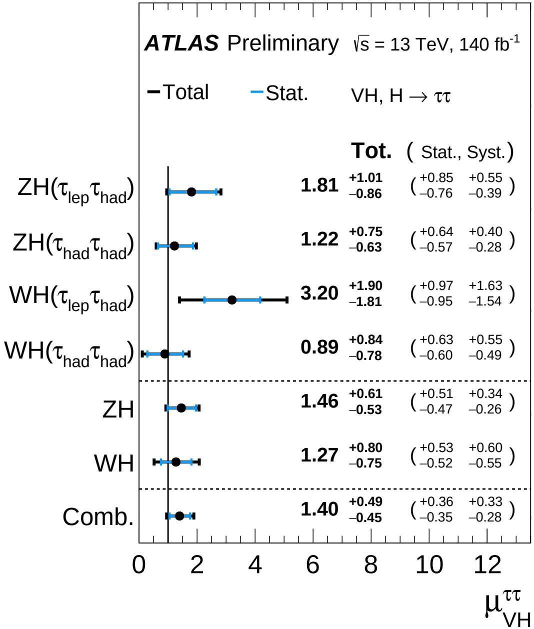
Backup

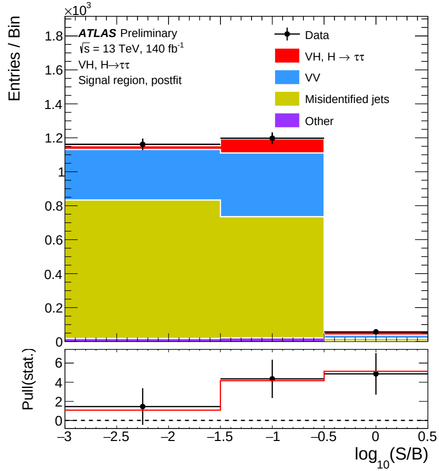
VH, $H \to \tau\tau$ *Fake* estimation

- *Fake Factor* is defined as $f = r/(1-r)$, where r represents the selection efficiency of misidentified objects (τ_{had} or light lepton)
  - measured in a dedicated Z+jets control region enriched in *Fake*
- Expected number of misidentified jets in a given region is obtained using the *Fake Factor* to scale the number of events selected in an orthogonal region in which one or more requirements are inverted
- Background modelling validation in several regions

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

$VH,\ H \to \tau\tau$ Cut-based analysis results





Significance (σ)	exp	obs
WH	1.4	1.7
ZH	2.2	3.1
Combined	2.5	3.5

Di-Higgs Combination arxiv-2211.01216

- Combination of $HH \to$bbbb, $HH \to$bb$\gamma\gamma$ and $HH \to$bb$\tau\tau$ final states
- 95% confidence limit (CL) on the di-Higgs cross-section normalised to SM prediction: $\mu_{HH} < 2.4\,(2.9)$ obs. (exp)
- Combination with single-Higgs measurements, with no constraint on other k, lead to k_λ constraint at 95% CL: $-1.4\,(-2.2) < k_\lambda < 6.1\,(7.7)$ obs. (exp)
- Constraint on k_{2V} at 95% CL: $0.1\,(0.0) < k_{2V} < 2.0\,(2.1)$ obs. (exp)