Searches for lepton flavour violation in Higgs boson decays, $H \to e\tau$ and $H \to \mu\tau$, at ATLAS

Antonio De Maria

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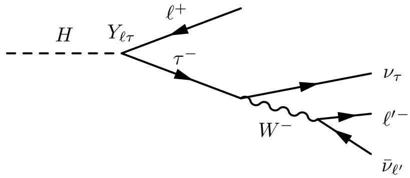
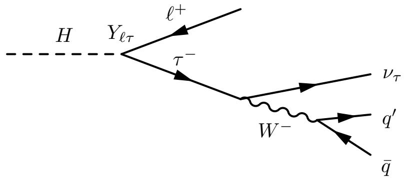
LFV $H \rightarrow l\tau$ decay search in ATLAS

- Analysis searching for two independent signal processes, $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$, considering both leptonic and hadronic τ decays
- For full leptonic final state ($\tau_{lep}\tau_{lep}$), $e\tau_{\mu}$ and $\mu\tau_{e}$, two different estimation methods for major backgrounds:
  - *MC-template* method: backgrounds estimated using Monte Carlo (MC) templates + normalisation through Control Regions (CRs)
  - *Symmetry* method: backgrounds estimated via data-driven symmetry method - More on this in Wu Minlin's talk
- For one lepton and one hadronically decaying τ final state ($\tau_{lep}\tau_{had}$) , $e\tau_{had}$ and $\mu\tau_{had}$, only *MC-template* method

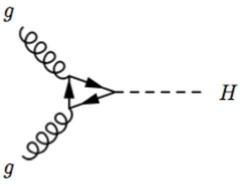


$e\tau_{\mu}$ and $\mu\tau_{e}$ search

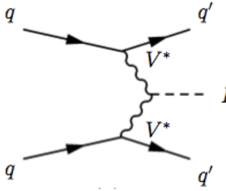


$e\tau_{had}$ and $\mu\tau_{had}$ search

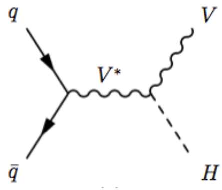
Event selection and categorisation



gluon fusion (ggF)



vector boson fusion (VBF)



associated production with a gauge boson (VH)

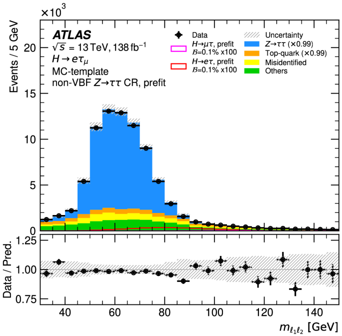
Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\mathrm{had}}$
VBF	*Baseline* ≥ 2 jets, $p_{\mathrm{T}}^{j_1} > 40\,\mathrm{GeV}$, $p_{\mathrm{T}}^{j_2} > 30\,\mathrm{GeV}$ $\lvert\Delta\eta_{jj}\rvert > 3$, $m_{jj} > 400\,\mathrm{GeV}$	
non-VBF	*Baseline* plus fail *VBF* categorisation – –	veto events if $90 < m_{\mathrm{vis}}(e, \tau_{\mathrm{had\text{-}vis}}) < 100\,\mathrm{GeV}$

- Cut-based signal region definition to enhance contribution from main Higgs boson production modes, *VBF*/*non-VBF*.
- MVA analysis in each signal region to enhance final sensitivity

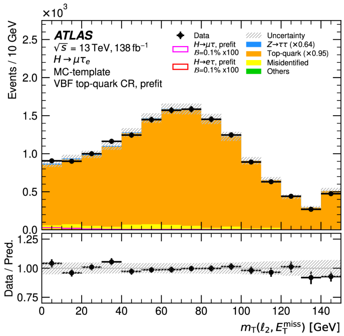
Background estimation in $\tau_{lep}\tau_{lep}$

- $Z \to \tau\tau$ and *Top* ($t\bar{t}$ + single-top) contribution estimated through templates + normalisation through 1-bin CRs separately for *VBF* and *non-VBF* categories
  - $Z \to \tau\tau$ CR: require lead lepton $p_T < 45$ GeV
  - Top CR: require at least 1 b-jet
- Diboson validated in a dedicated region
- Other minor backgrounds estimated from MC
- Misidentified background (*Fake*) estimated via *ABCD* method using lepton charge and isolation

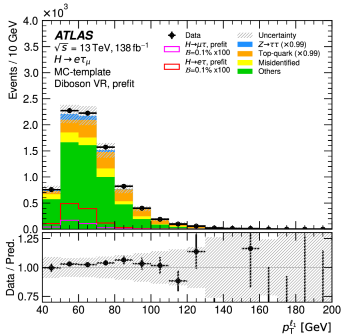
Non-VBF, $Z \to \tau\tau$ CR



VBF, Top CR



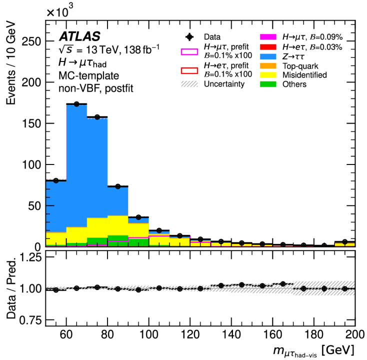
Diboson VR



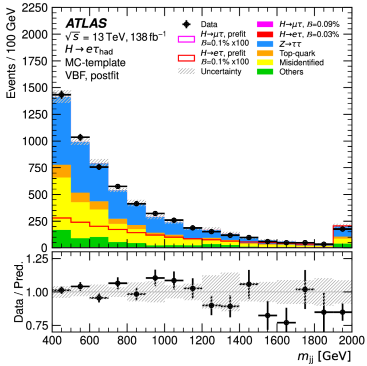
Background estimation in $\tau_{lep}\tau_{had}$

- $Z \rightarrow \tau\tau$ contribution estimated with templates + independent Norm Factors (NFs) for *VBF* and *non-VBF* categories
- *Top* contribution estimated through templates and normalisation through shared NFs with $\tau_{lep}\tau_{lep}$
- Other minor backgrounds estimated from MC
- Fake estimated through *Fake-Factor* method based on hadronic τ identification

Non-VBF, SR

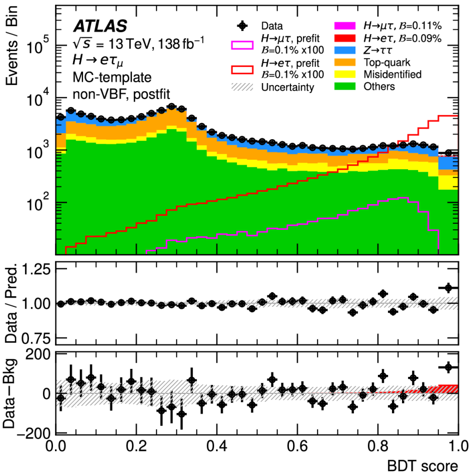


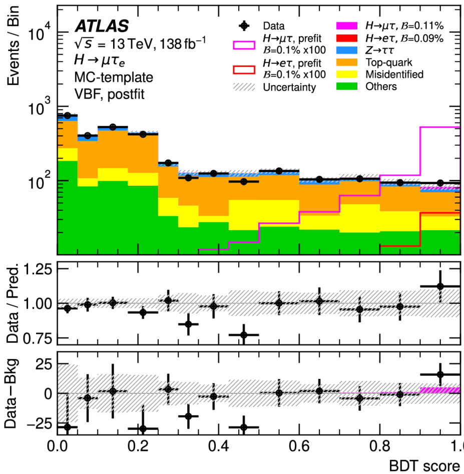
VBF, SR



MVA analysis strategy in $\tau_{lep}\tau_{lep}$

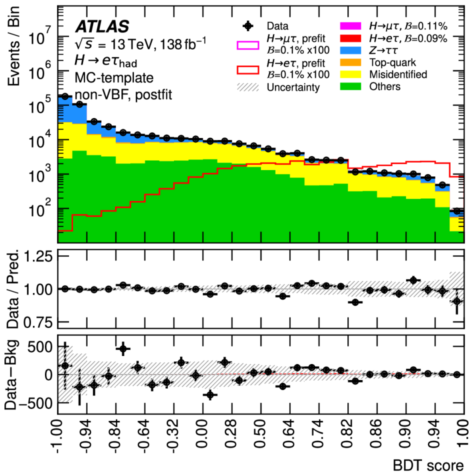
- Boosted Decision Trees (BDTs) trained separately for *VBF* and *non-VBF* categories, but summing over $e\tau_\mu$ and $\mu\tau_e$ final states
  - 3 BDTs combined linearly (Signal Vs Z/H→ $\tau\tau$ + Z→ *ll*, Signal Vs Top + Diboson + H→ *WW*, Signal Vs Fake)

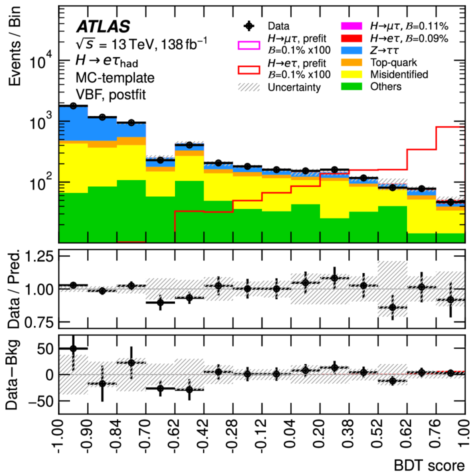




MVA analysis strategy in $\tau_{lep}\tau_{had}$

- BDTs trained separately for *VBF*, *non-VBF* categories and for $e\tau_{had}$, $\mu\tau_{had}$ final states
  - *non-VBF* $e\tau_{had}$: 3 BDTs combined linearly (Signal Vs Z$\rightarrow \tau\tau$, Signal Vs Fake, Signal Vs all other backgrounds)
  - VBF category and *non-VBF* $\mu\tau_{had}$: 2 BDTs combined linearly for *non-VBF* $\mu\tau_{had}$ and quadratically for VBF category (Signal Vs Z$\rightarrow \tau\tau$, Signal Vs all other backgrounds)





Fit analysis strategy

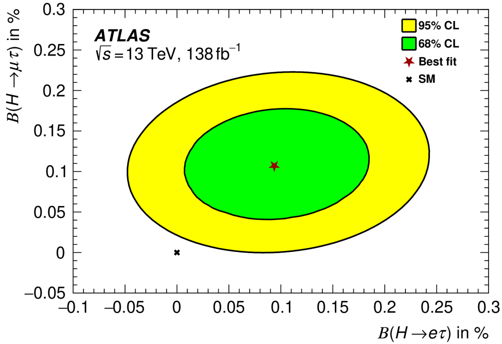
Method	Channel	Category	Region	1 POI fit	2 POI fit
MC-template	$\ell\tau_{\ell'}$	*non-VBF*	SR	✓	✓
			$Z \to \tau\tau$ CR	✓	✓
			Top-quark CR	✓	✓
		VBF	SR		✓
			$Z \to \tau\tau$ CR		✓
			Top-quark CR		✓
MC-template	$\ell\tau_{\text{had}}$	*non-VBF*	SR	✓	✓
		VBF	SR	✓	✓
Symmetry	$\ell\tau_{\ell'}$	*non-VBF*	SR		
		VBF	SR	✓	

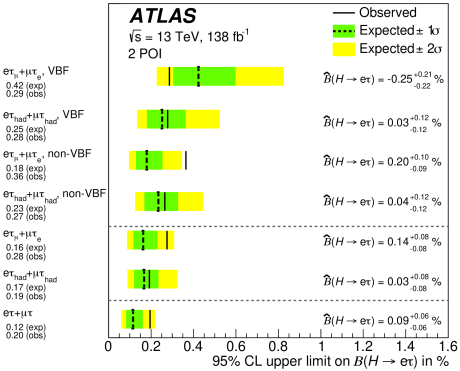
- Use MVA outputs for each category as final discriminant in the fit to extract the signal strength and upper limits at 95% confidence limits (C.L.)

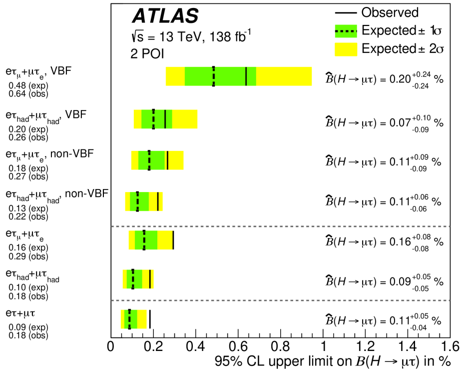
- Different types of fit performed to extract results; next slides focus on *2 POI* fit:
  - *2 POI*: simultaneous fit of $\mathcal{B}r(H \to \mu\tau)$ and $\mathcal{B}r(H \to e\tau)$. No assumption on $\mathcal{B}r$

2 POI fit results

- 2.4 σ excess observed for $\mathcal{B}r(H \to \mu\tau)$ and 1.6 σ for $\mathcal{B}r(H \to e\tau)$
- Compatibility with SM within 2.1 σ
- Observed (expected) upper limits at 95% C.L. on $\mathcal{B}r$ are 0.20% (0.12%) for $H \to e\tau$ and 0.18% (0.09 %) for $H \to \mu\tau$





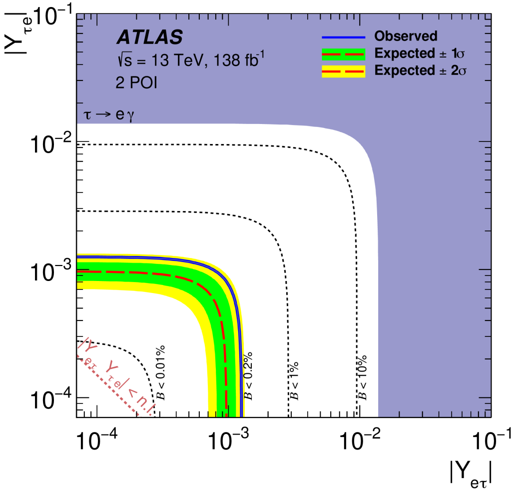


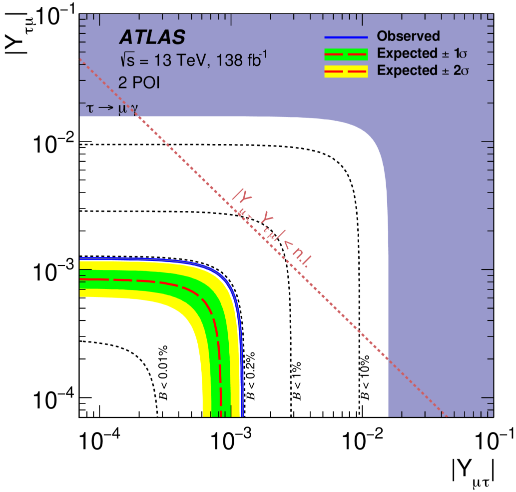
Interpretation as Yukawa-coupling

- $\mathcal{B}r$ values can be related to non-diagonal Yukawa coupling matrix elements:

$$|Y_{l\tau}|^2 + |Y_{\tau l}|^2 = \frac{8\pi}{m_H} \frac{\mathcal{B}r(H \to l\tau)}{1 - \mathcal{B}r(H \to l\tau)} \Gamma_H(\text{SM})$$

- From 2POI fit, $\sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 0.0013$ and $\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 0.0012$



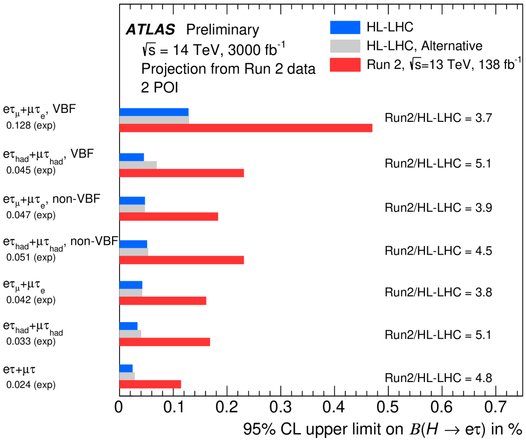


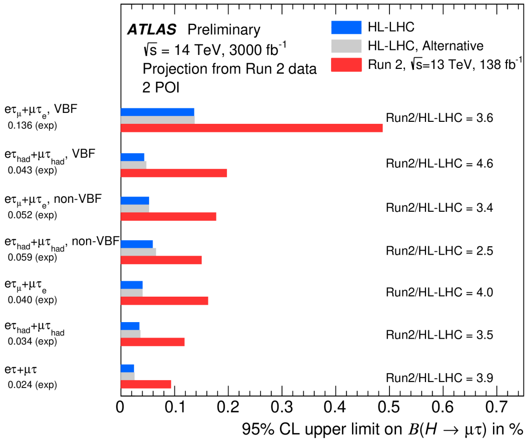
2 POI fit uncertainty breakdown

2 POI Source of uncertainty	Impact on observed $[10^{-4}]$ $\hat{\mathcal{B}}(H \to e\tau)$	 $\hat{\mathcal{B}}(H \to \mu\tau)$
Flavour tagging	0.7	0.2
Misidentified background ($e\tau_{\text{had}}$)	2.1	0.3
Misidentified background ($e\tau_{\mu}$)	2.7	0.3
Misidentified background ($\mu\tau_{\text{had}}$)	0.6	1.4
Misidentified background ($\mu\tau_{e}$)	0.9	1.0
Jet and $E_{\text{T}}^{\text{miss}}$	1.2	0.9
Electrons and muons	1.4	0.5
Luminosity	0.6	0.4
Hadronic τ decays	0.9	0.9
Theory (signal)	0.8	0.8
Theory (Z + jets processes)	0.8	1.0
$Z \to \ell\ell$ normalisation ($e\tau$)	<0.1	<0.1
$Z \to \ell\ell$ normalisation ($\mu\tau$)	0.2	0.9
Background sample size	3.7	2.3
Total systematic uncertainty	5.1	3.6
Data sample size	3.0	2.7
Total	5.9	4.5

- Analysis dominated by systematic uncertainties, mainly from background sample statistics and Fake background estimation

Projecting results to HL-LHC Note





- Starts from Run2 analysis results and extrapolate to HL-LHC scenario
- Expect to improve current limits by factor 4 (5) for $\mathcal{B}r(H \to \mu\tau)$ ($\mathcal{B}r(H \to e\tau)$)
- Strong push to re-consider the analysis trying to reduce the impact of the systematic uncertainties/MC Statistics

Conclusion

- A search for two LFV signals , $H \to e\tau$ and $H \to \mu\tau$, has been presented
- From simultaneous fit of the $H \to e\tau$ and $H \to \mu\tau$ signal, observed (expected) upper limits at 95% C.L. on the branching ratios are 0.20% (0.12%) for $H \to e\tau$ and 0.18% (0.09 %) for $H \to \mu\tau$; compatibility with SM within 2.1 σ
- Observed limits improved by factors of up to 2.4 (1.5) than the corresponding limits for the $H \to e\tau$ ($H \to \mu\tau$) decay from previous ATLAS results. Expected sensitivity for $H \to e\tau$ ($H \to \mu\tau$) signal improved by a factor of about 3.1 (4.1)
- Results also extrapolated for HL-LHC scenario: improve current limits by factor 4 (5) for $\mathcal{B}r(H \to \mu\tau)$ ($\mathcal{B}r(H \to \mathrm{e}\tau)$)

Thanks For Your Attention

Backup

Baseline and SRs event selection

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly 1e and 1μ, OS τ_{had}-veto b-veto $p_{\text{T}}^{\ell_1} > 45\,(35)$ GeV MC-template (Symmetry method) $p_{\text{T}}^{\ell_2} > 15$ GeV 30 GeV $< m_{\ell_1\ell_2} <$ 150 GeV $0.2 < p_{\text{T}}^{\text{track}}(\ell_2 = e)/p_{\text{T}}^{\text{cluster}}(\ell_2 = e) < 1.25$ (MC-template) track d_0 significance requirement (see text) $\lvert z_0 \sin\theta\rvert < 0.5$ mm	exactly 1ℓ and 1$\tau_{\text{had-vis}}$, OS τ_{had} Tight ID Medium eBDT ($e\tau_{\text{had}}$) b-veto $p_{\text{T}}^{\ell} > 27.3$ GeV $p_{\text{T}}^{\tau_{\text{had-vis}}} > 25$ GeV, $\lvert\eta^{\tau_{\text{had-vis}}}\rvert < 2.4$ $\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_{\text{T}}^{\text{miss}}) > -0.35$ $\lvert\Delta\eta(\ell, \tau_{\text{had-vis}})\rvert < 2$
VBF	*Baseline* ≥ 2 jets, $p_{\text{T}}^{j_1} > 40$ GeV, $p_{\text{T}}^{j_2} > 30$ GeV $\lvert\Delta\eta_{jj}\rvert > 3$, $m_{jj} > 400$ GeV	
non-VBF	*Baseline* plus fail *VBF* categorisation – –	 veto events if $90 < m_{\text{vis}}(e, \tau_{\text{had-vis}}) < 100$ GeV

2POI Fit model scheme