Searches for lepton-flavour-violating decays of the Higgs boson into e-τ and μ-τ in ATLAS

ATLAS-CONF-2022-060

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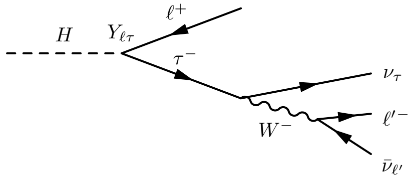
on the behalf of the ATLAS collaboration

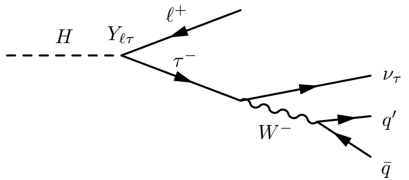
Higgs Hunting 2022

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

- Analysis searching for two independent signals, $H \to e\tau$ and $H \to \mu\tau$, considering both hadronic and leptonic τ decays
- Full leptonic final state (*leplep*), $e\tau_\mu$ and $\mu\tau_e$, considering 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
- One lepton and one hadronically decaying τ final state (*lephad*) , $e\tau_{had}$ and $\mu\tau_{had}$, considering only *MC-template* method
- First time these results are shown in a conference

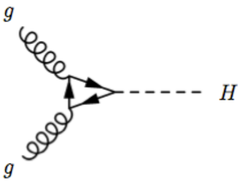


$e\tau_\mu$ and $\mu\tau_e$ search

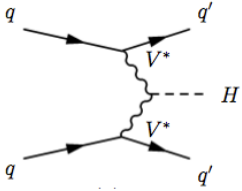


$e\tau_{had}$ and $\mu\tau_{had}$ search

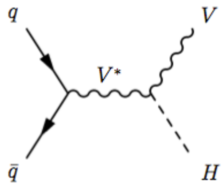
Event selection and categorisation



gluon fusion (ggF)



vector boson fusion (VBF)



associated production with a gauge boson (VH)

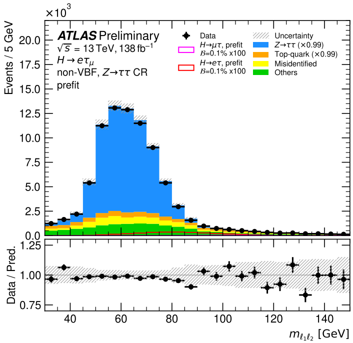
Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\mathrm{had}}$
	Baseline	
VBF	≥ 2 jets, $p_{\mathrm{T}}^{j_1} > 40\,\mathrm{GeV}$, $p_{\mathrm{T}}^{j_2} > 30\,\mathrm{GeV}$	
	$\lvert\Delta\eta_{jj}\rvert > 3$, $m_{jj} > 400\,\mathrm{GeV}$	
	Baseline plus fail *VBF* categorisation	
non-VBF	–	veto events if
	–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

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

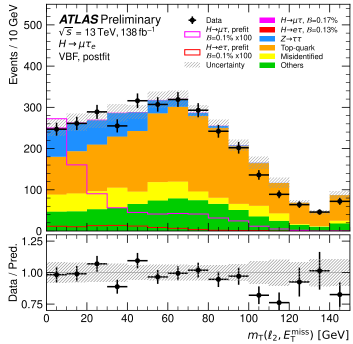
Background estimation for *MC-Template* method in leplep final state

- $Z \to \tau\tau$ and *Top* ($t\bar{t}$ + single-top) contribution estimated through templates + normalisation through 1-bin CRs separately for *VBF* and *non-VBF* categories
  - Top CR: require at least 1 b-jet
  - $Z \to \tau\tau$ CR: require lead lepton $p_T < 45$ GeV
- $Z \to \mu\mu$ background estimated with templates + prefit normalisation and related uncertainty from dedicated CR
- 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, SR

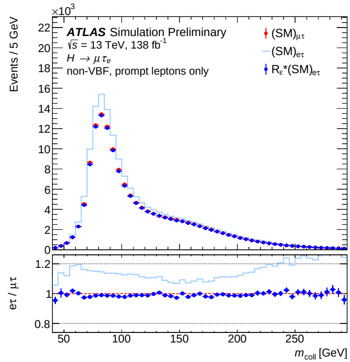


Symmetry background estimation in leplep final state

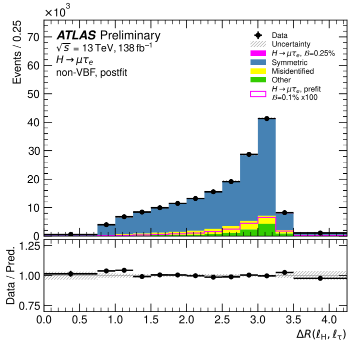
Link

- Based on the assumption that SM processes are symmetric with respect to e $\leftrightarrow$ μ exchange
- LFV H decays break this symmetry if $\mathcal{B}r(H \to \mu\tau)$ different from $\mathcal{B}r(H \to e\tau)$
- Use data from one channel to make background prediction for the other channel, after correcting for biases due to experimental effects
- Fakes estimated through *FakeFactor* (FF) based on lepton identification
- Method sensitive to $\mathcal{B}r$ differences between two LFV signals; if one $\mathcal{B}r$ assumed to be 0, then analysis measures absolute $\mathcal{B}r$ value

Non-VBF, SR



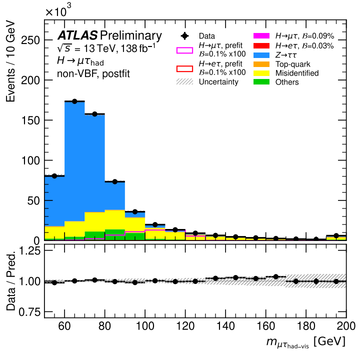
Non-VBF, SR



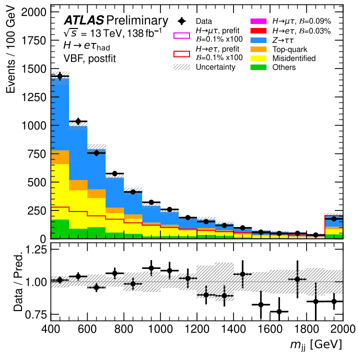
Background estimation for *MC-Template* method in lephad final state

- $Z \rightarrow \tau\tau$ 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 leplep in MC-Template fit, or fixed to MC
- $Z \rightarrow \mu\mu$ background estimated with templates + prefit normalisation and related uncertainty from dedicated CR
- Other minor backgrounds estimated from MC
- Fake estimated through FF method based on hadronic τ identification

Non-VBF, SR

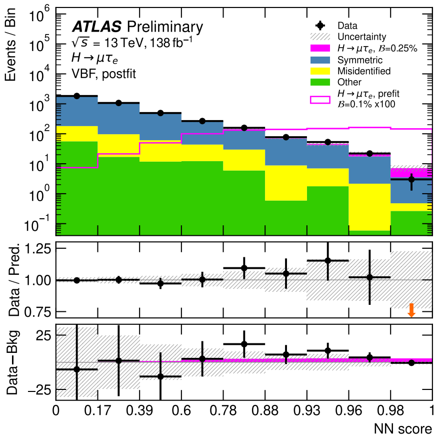


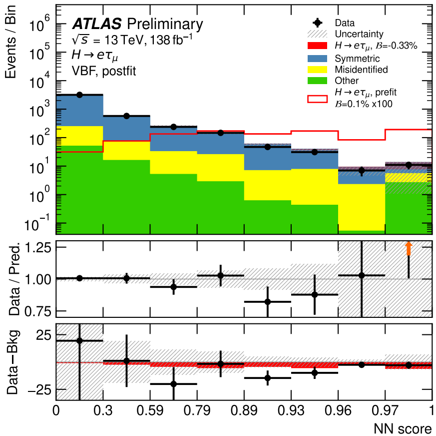
VBF, SR



MVA analysis strategy

- Different strategies developed for the different final states/methods
- Symmetry method: Neural Networks (NNs) trained separately for *VBF* and *non-VBF* categories, but summing over $e\tau_\mu$ and $\mu\tau_e$ final states
  - for *non-VBF* category: one NN with 3 nodes $\rightarrow$ signal node used for fit
  - for VBF category: three NNs combined linearly (Signal Vs Z/H$\rightarrow \tau\tau$+MC fakes, Signal Vs Top + Diboson + H$\rightarrow$ *WW*, Signal Vs Fake)

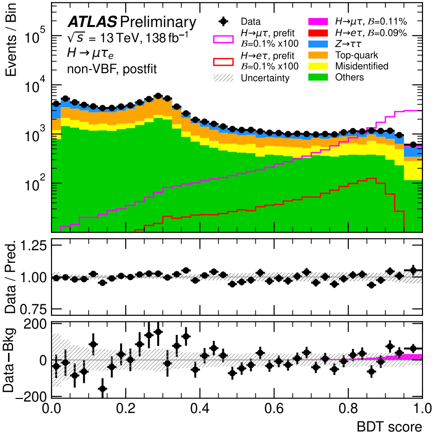


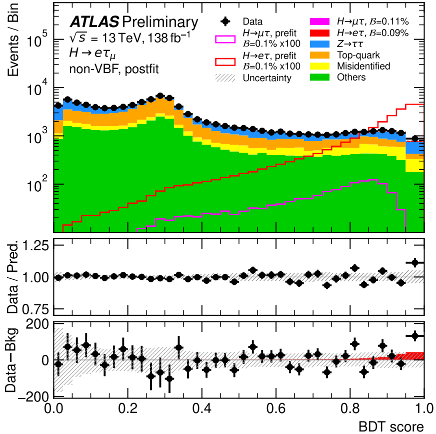


- *Negative* signal for $e\tau_\mu$ for Symmetry method expected due to anticorrelation of $\mathcal{B}r(H \rightarrow \mu\tau)$ and $\mathcal{B}r(H \rightarrow e\tau)$

MVA analysis strategy

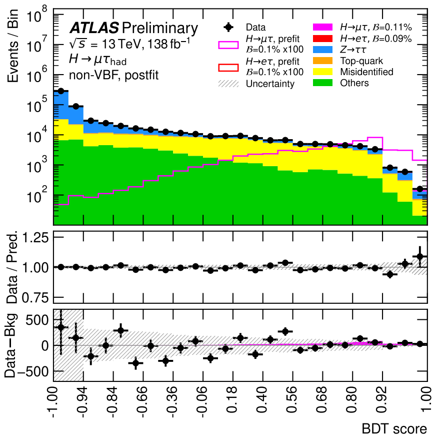
- Different strategies developed for the different final states/methods
- MC-template leplep: Boosted Decision Trees (BDTs) trained separately for *VBF* and *non-VBF* categories, but summing over $e\tau_\mu$ and $\mu\tau_e$ final states
  - 3 BDTs combined linearly (Signal Vs Z/H$\rightarrow \tau\tau$ + Z$\rightarrow$ *ll*, Signal Vs Top + Diboson + H$\rightarrow$ *WW*, Signal Vs Fake)

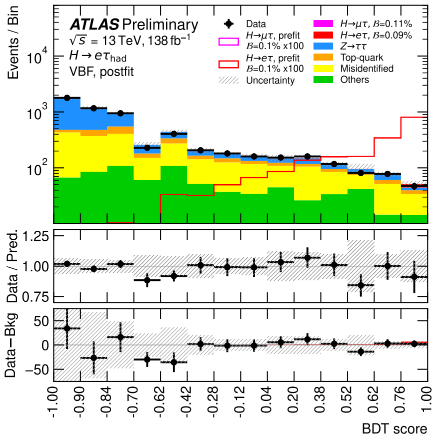




MVA analysis strategy

- Different strategies developed for the different final states/methods
- MC-template lephad: 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)



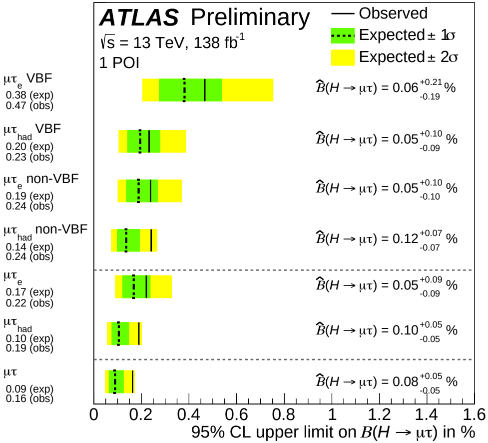


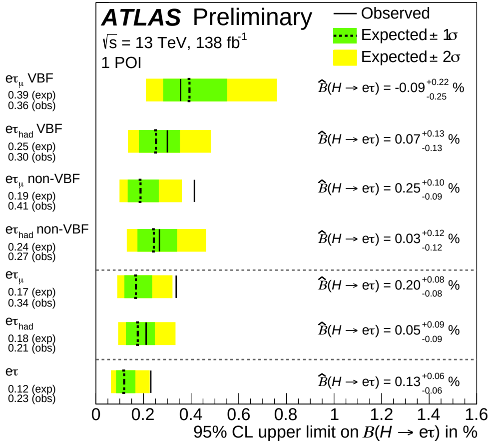
Fit analysis strategy

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.)
- Three different type of fit:
  - *1 POI*: independent fit of $\mathcal{B}r(H \to \mu\tau)$ and $\mathcal{B}r(H \to e\tau)$, assuming one $\mathcal{B}r = 0$ when fitting the other $\mathcal{B}r$. Use a combination of Symmetry and MC-Template method
  - $\mathcal{B}r$ difference in leplep channel: remove the assumption of one $\mathcal{B}r = 0$
  - *2 POI*: simultaneous fit $\mathcal{B}r(H \to \mu\tau)$ and $\mathcal{B}r(H \to e\tau)$. Use only MC-Template method and remove the assumption of one $\mathcal{B}r = 0$

1 POI fit results

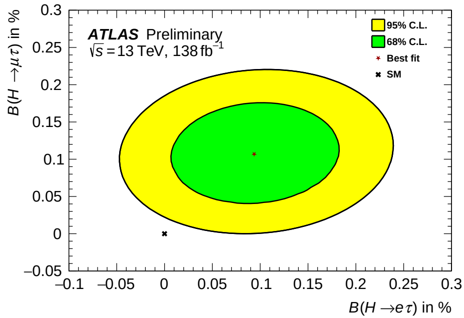


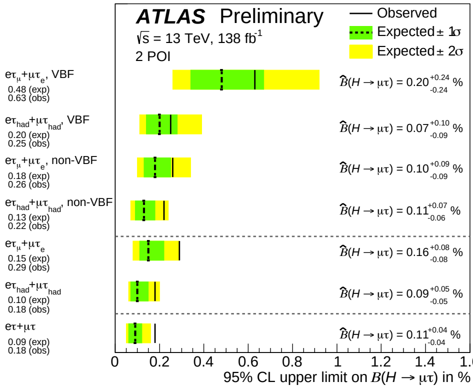


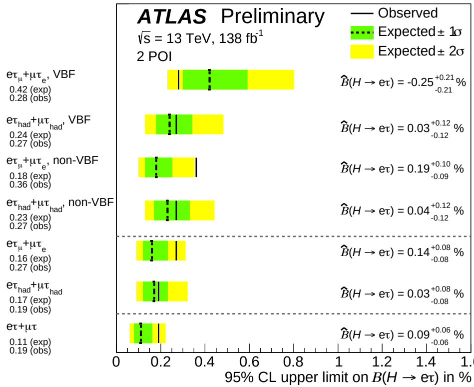
- Observed limits above the expected ones for both $H \to e\tau$ and $H \to \mu\tau$ signals
- 1.9 σ excess observed for $\mathcal{B}r(H \to \mu\tau)$ while 2.2 σ for $\mathcal{B}r(H \to e\tau)$
  - excess in $H \to \mu\tau$ ($H \to e\tau$) driven by *non-VBF* category of lephad (leplep) channel

2 POI fit results

- 2.5 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 2.2 σ
- Observed (expected) upper limits at 95% C.L. on $\mathcal{B}r$ are 0.19% (0.11%) for $H \to e\tau$ and 0.18% (0.09 %) for $H \to \mu\tau$





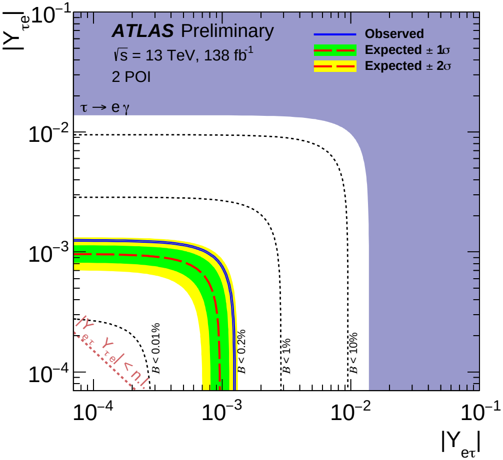


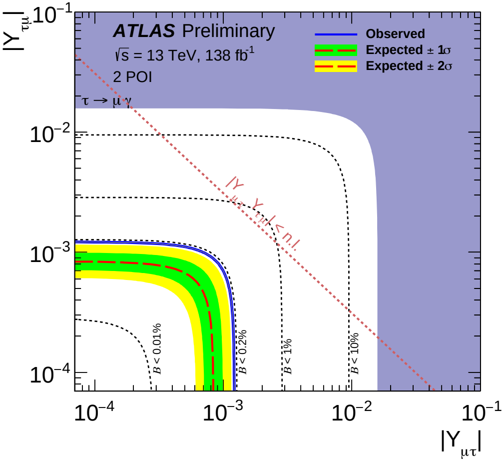
Interpretation as Yukawa-coupling

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

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

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





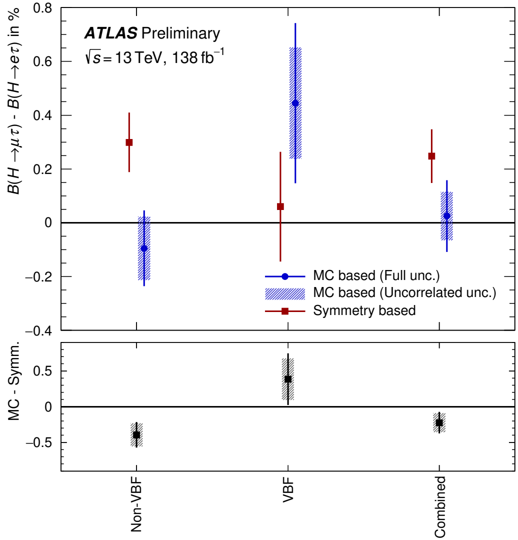
2 POI fit uncertainty breakdown

2 POI Source of uncertainty	Impact ($\times 10^2$) on observed $\hat{\mathcal{B}}(H \to e\tau)$	 $\hat{\mathcal{B}}(H \to \mu\tau)$
Flavour tagging	0.007	0.003
Misidentified background ($e\tau_{\mathrm{had}}$)	0.021	0.003
Misidentified background ($e\tau_{\mu}$)	0.058	0.003
Misidentified background ($\mu\tau_{\mathrm{had}}$)	0.006	0.015
Misidentified background ($\mu\tau_{e}$)	0.009	0.011
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	0.012	0.009
Electrons and muons	0.013	0.005
Luminosity	0.007	0.005
Hadronic τ decays	0.009	0.009
Theory (signal)	0.007	0.007
Theory (Z + jets processes)	0.007	0.009
$Z \to \ell\ell$ normalisation ($e\tau$)	<0.001	<0.001
$Z \to \ell\ell$ normalisation ($\mu\tau$)	0.002	0.007
Background sample size	0.037	0.023
Total systematic uncertainty	0.051	0.036
Data sample size	0.030	0.027
Total	0.059	0.045

- Analysis dominated by systematic uncertainties, mainly from background sample statistics and Fake background estimation
- Similar conclusion also for 1POI fit

$\mathcal{B}r$ difference measurement

- Symmetry method measures the $\mathcal{B}r(H \to \mu\tau)$ - $\mathcal{B}r(H \to e\tau)$ difference, if no assumption on one $\mathcal{B}r = 0$ is imposed
- Combining VBF and Non-VBF categories, $\mathcal{B}r(H \to \mu\tau)$- $\mathcal{B}r(H \to e\tau)$ $= 0.25 \pm 0.10$ %
- Symmetry results are compared with 2 POI fit of the MC-template leplep channel
- Compatibility between the two different methods is found to be within 2.3σ



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 0.19% (0.11%) for $H \to e\tau$ and 0.18% (0.09 %) for $H \to \mu\tau$; compatibility with SM within 2.2 σ
- Results can be also interpreted as limit on the non-diagonal Yukawa coupling matrix elements, $\sqrt{|Y_{\tau e}|^2 + |Y_{e\tau}|^2} < 0.0012$ and $\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} < 0.0012$
- $\mathcal{B}r$ difference in leplep channel has also been measured $\mathcal{B}r(H \to \mu\tau)$-$\mathcal{B}r(H \to e\tau) = 0.25\pm0.10$ %, indicating small but not significant fluctuations
- 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)

Thanks For Your Attention

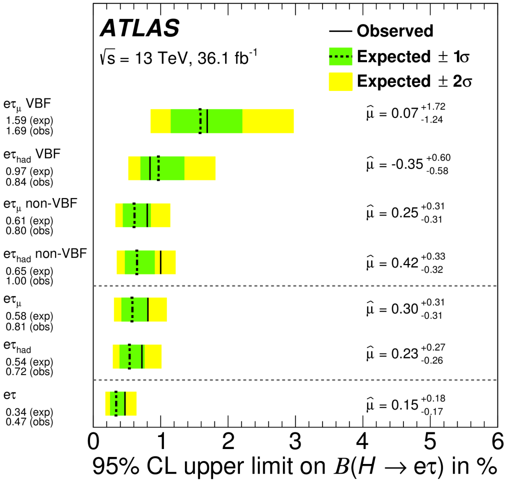
Backup

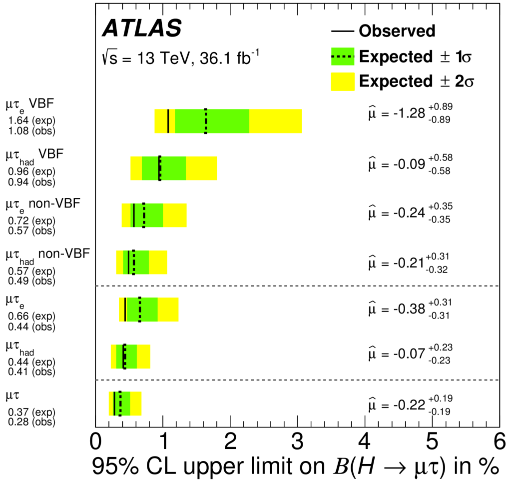
Baseline and SRs event selection

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 $30\,\text{GeV} < m_{\ell_1\ell_2} < 150\,\text{GeV}$ $0.2 < p_{\text{T}}^{\text{track}}(\ell_2 = e)/p_{\text{T}}^{\text{cluster}}(\ell_2 = e) < 1.25$ (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, $p_{\text{T}}^{\text{j}_1} > 40$ GeV, $p_{\text{T}}^{\text{j}_2} > 30$ GeV $\lvert\Delta\eta_{\text{jj}}\rvert > 3$, $m_{\text{jj}} > 400$ GeV	
non-VBF	*Baseline* plus fail *VBF* categorisation – –	 veto events if $90 < m_{\text{vis}}(e, \tau_{\text{had-vis}}) < 100$ GeV

- Similar selection between MC-template and Symmetry; differences related to the symmetry assumption and definition of CRs.

Previous limits for LFV $H \to l\tau$ search





- Analysis based on 2015+2016 dataset, 36 fb^{-1}

CMS limits for LFV $H \to l\tau$ search