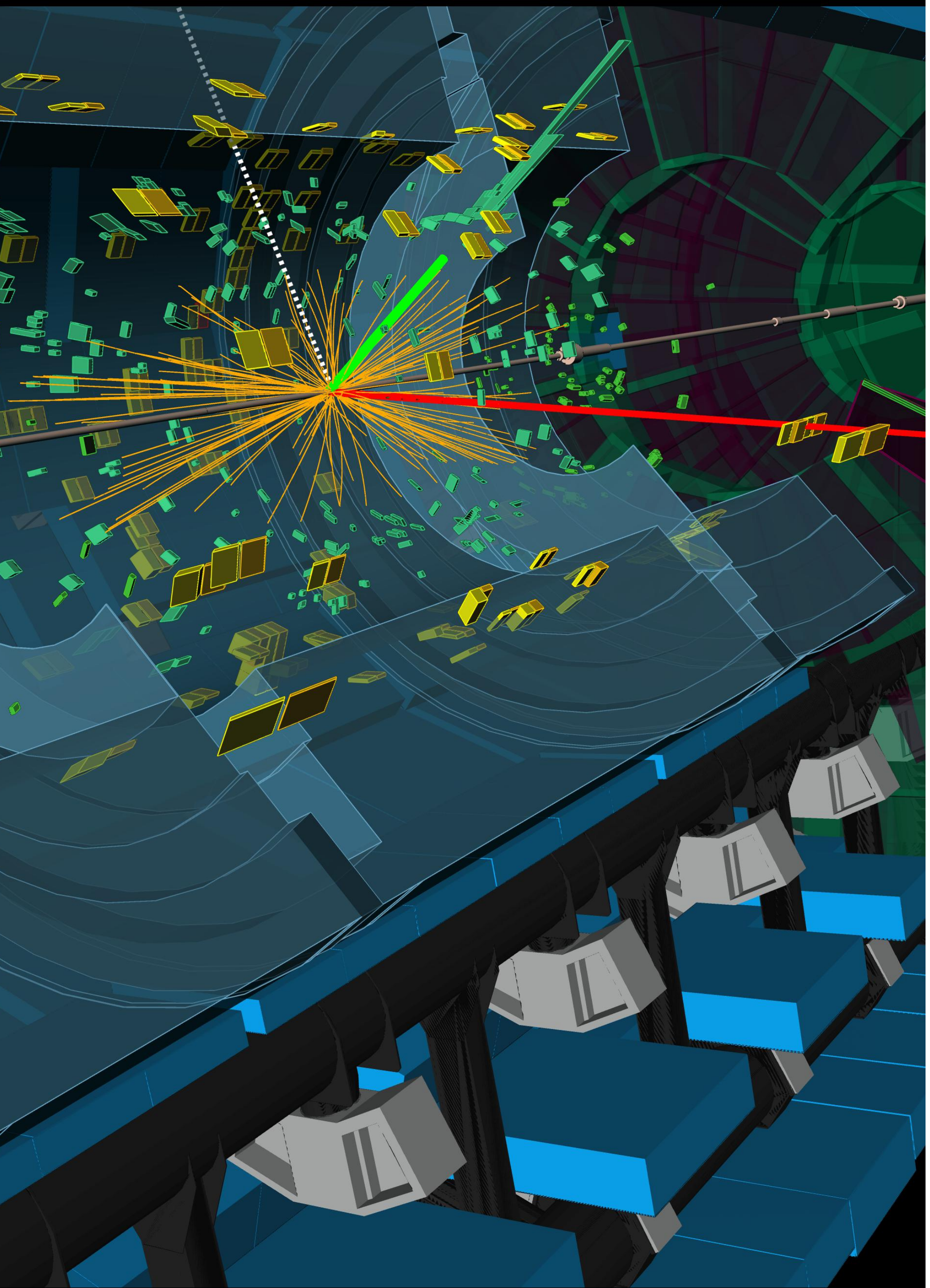

Searches for lepton-flavor-violating decays of the Higgs boson into $e\tau$ and $\mu\tau$ in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

7th RED LHC workshop

Antonio Jesús Gómez Delegido

arXiv:2302.05225

ATLAS EXPERIMENT

IFIC INSTITUT DE FÍSICA CORPUSCULAR

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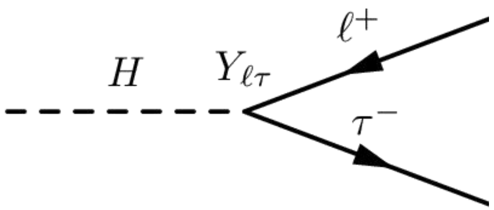
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Motivation

- **Lepton flavour conservation** is accidental in the **SM**. Neutrino oscillations exhibit that Lepton Flavour Violating (LFV) processes do occur in nature. LFV processes also in charged lepton sector?

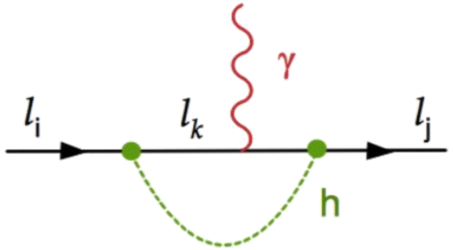


- LFV decays of the Higgs boson expected in several SM extensions (SUSY, 2HDM, composite Higgs...). **Low energy results** provide **constraints**.

	Indirect			Direct	
H decay	Upper Limit	Process	Reference	Upper Limit	Reference
$H \to e\mu$	$\mathcal{O}(10^{-13})$	$\mu \to e\gamma$	[1303.0754]	0.061 %	ATLAS 139 fb^{-1} [1909.10235]
$H \to e\tau$	$\mathcal{O}(10\%)$	$\tau \to e\gamma$	[0908.2381]	0.22 %	CMS 137 fb^{-1} [2105.03007]
$H \to \mu\tau$	$\mathcal{O}(10\%)$	$\tau \to \mu\gamma$	[0908.2381]	0.15%	CMS 137 fb^{-1} [2105.03007]

- Information from $\mu \to e\gamma$ and $\mu \to e$ conversion in nuclei correlate $H \to e\tau$ and $H \to \mu\tau$ decays [JHEP 06 (2015) 108].

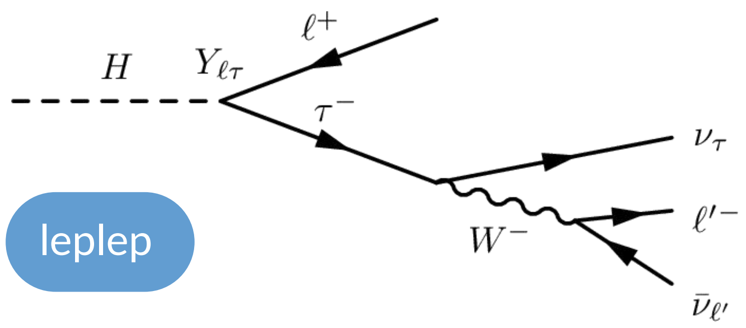
$$\mathcal{B}(h \to \tau\mu) \times \mathcal{B}(h \to \tau e) = \left[\frac{m_h}{8\pi\Gamma_h}\right]^2 \left(\frac{\mathcal{B}(\mu \to e\gamma)}{\mathcal{B}_0^{\mu\to e\gamma}} + \frac{\mathcal{B}(\mu \to e)_{\text{Au}}}{\mathcal{B}_0^{\mu e}}\right)$$
$$= 7.95 \times 10^{-10} \left[\frac{\mathcal{B}(\mu \to e\gamma)}{10^{-13}}\right] + 3.15 \times 10^{-4} \left[\frac{\mathcal{B}(\mu \to e)_{\text{Au}}}{10^{-13}}\right]$$

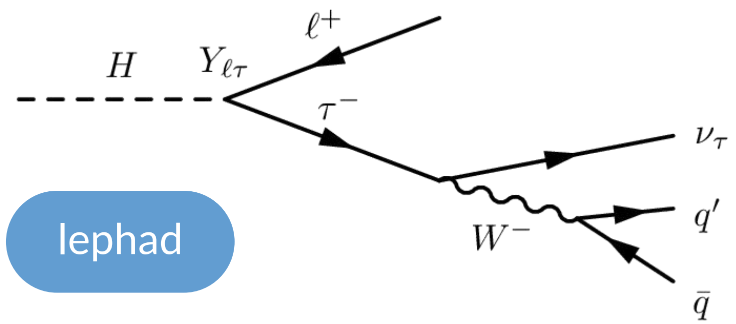


Dominant term, since $\mathcal{B}(\mu \to e)_{\text{Au}} < 7 \times 10^{-13}$ [Eur.Phys.J. C47, 337 (2006)]

Analysis introduction

- $H \to e\tau$ and $H \to \mu\tau$ are **independent signals** (two searches). Two analyses targeting **leptonic τ decays** (different background estimation) and one for **hadronic τ decays**.





- Different analyses based on background estimation and final state:

Symmetry based leplep	Fake background data-driven. Other backgrounds estimated mainly via data-driven symmetry method
MC-template leplep	Fake background data-driven. Other backgrounds estimated with MC templates and normalization of main backgrounds estimated data-driven from CRs
MC-template lephad	Fake background data-driven. Other backgrounds estimated through MC with normalization coming from leplep CRs if fit combines both channels.

Event selection and categorization

- **Main** Higgs boson **production modes** considered for LFV signal: gluon fusion, vector boson fusion (VBF), vector boson associated production.
- General strategy: **loose preselection** and further cut-based **categorization** into **VBF** and **Non VBF** regions. Simplified description below. Detailed selection in backup

Selection	leplep	lephad
Baseline	$1e$ and 1μ with opposite sign. No hadronic τ	$1e$ or 1μ and 1 hadronic τ with opposite sign
	b-veto	
VBF	$N_{\text{jets}} > 2$	
Non-VBF	Fail VBF selection	

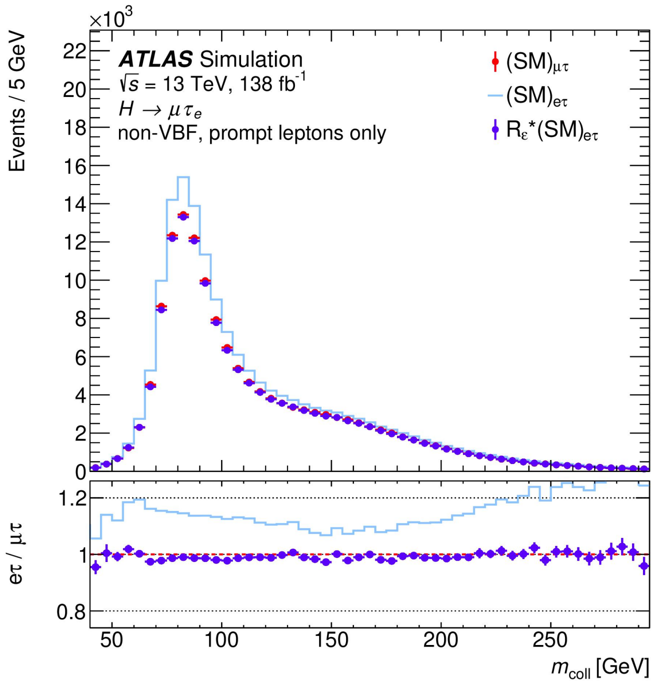
- leplep final state with one electron and one muon ($e\tau_{\mu}$ or $\mu\tau_{e}$). **Channel classification** based on $\boldsymbol{p_{\mathrm{T}}}$ **ordering** in **approximate Higgs** boson **rest frame** ($p_{\mathrm{T}}(\ell_{H}) > p_{\mathrm{T}}(\ell_{\tau})$).
- Additional **CRs** dependent on the analysis to extract **normalization** of **top-quark** and $\boldsymbol{Z \to \tau\tau}$ backgrounds.
- **Multivariate analyses (MVA)** used to **enhance sensitivity**. Final discriminants for fit built from MVA outputs.

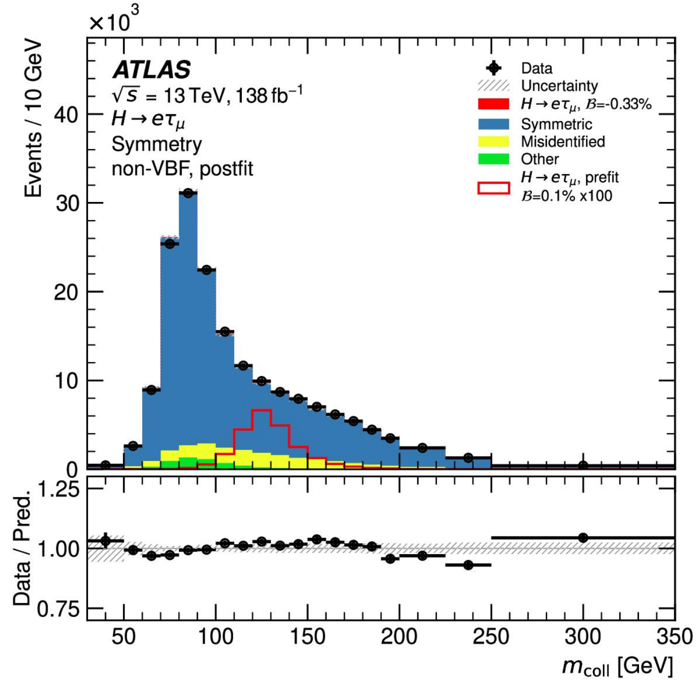
Background estimation with the symmetry method

Symmetry based leplep

- Data-driven search were the background in one channel is estimated using the data yields in the other channel [Phys.Rev.D 90, 015025 (2014)].
  - Standard Model processes are symmetric with respect $e \longleftrightarrow \mu$ exchange.
  - LFV decays of the Higgs boson where $\mathcal{B}(H \rightarrow e\tau) \neq \mathcal{B}(H \rightarrow \mu\tau)$ break this symmetry.
  - Split data in two samples $(e\tau, \mu\tau)$. Correct induced asymetries (experimental efficiencies and different rates for misidentified objects). Use **one sample as background estimation of the other.**

- If **signal** is present in **one channel**, then a **deficit** should be observed **in the other**.
- Mis-identified objects estimated through fake factor method based on lepton identification.
- If there is no assumption on the branching ratios, the method is **sensitive** to **branching ratio difference**.

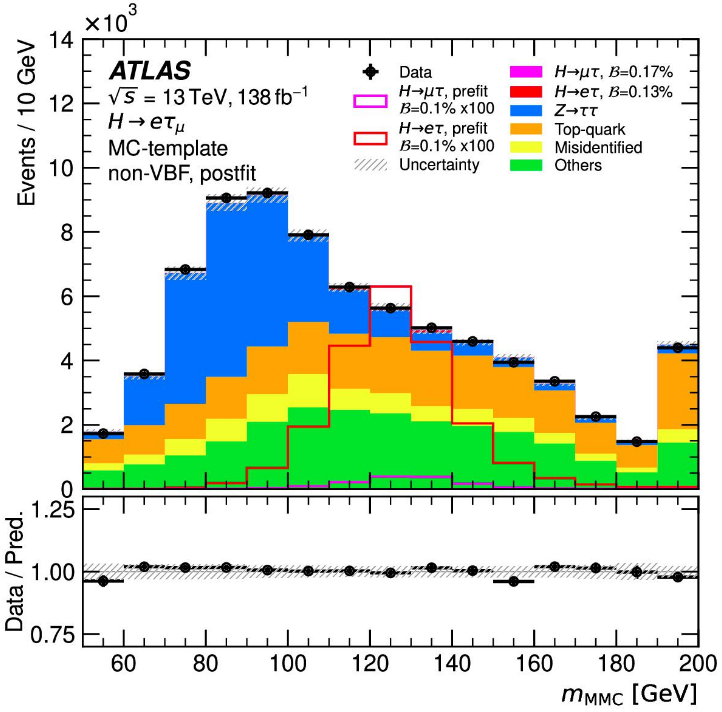


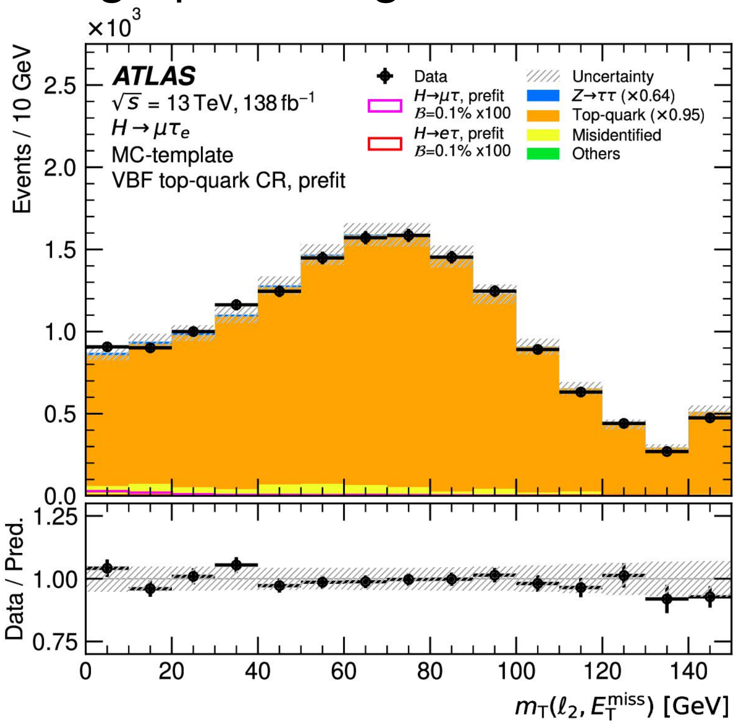


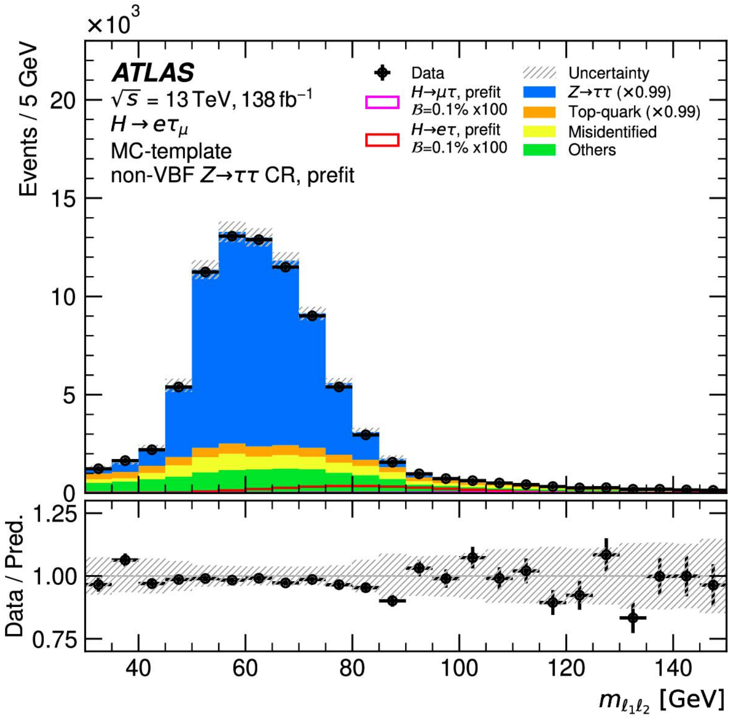
Background estimation with MC-templates

MC-template leplep

- $\boldsymbol{Z \to \tau\tau}$ **and top-quark background** estimated through MC templates. Normalization extracted from 1-bin control regions (CRs) in fit separately for VBF and non-VBF. Shared between $e\tau$ and $\mu\tau$ in 2POI fit.
- $\boldsymbol{Z \to \mu\mu}$. Estimated with MC templates. Normalization (and related uncertainty) extracted from dedicated CR. Applied at pre-fit level.
- Other minor backgrounds estimated from MC. Diboson modelling checked in dedicated validation region.
- **Fakes**. Data-driven ABCD method using lepton charge and isolation.



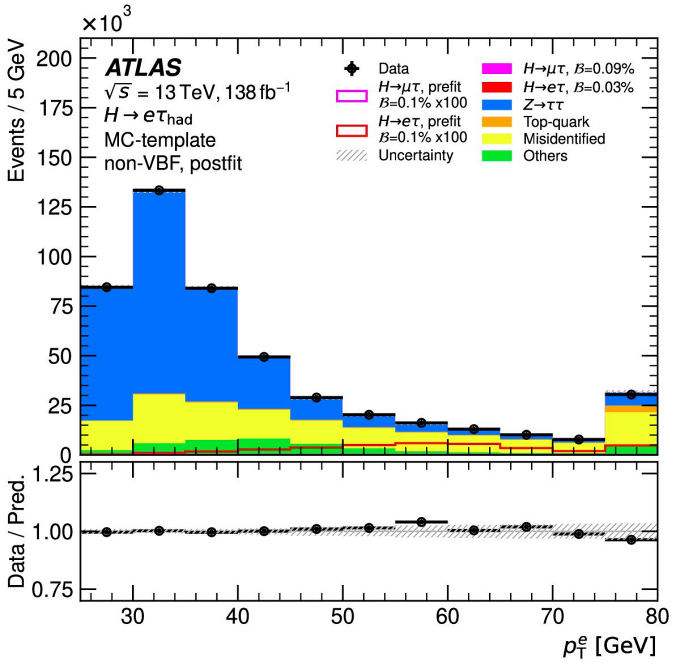


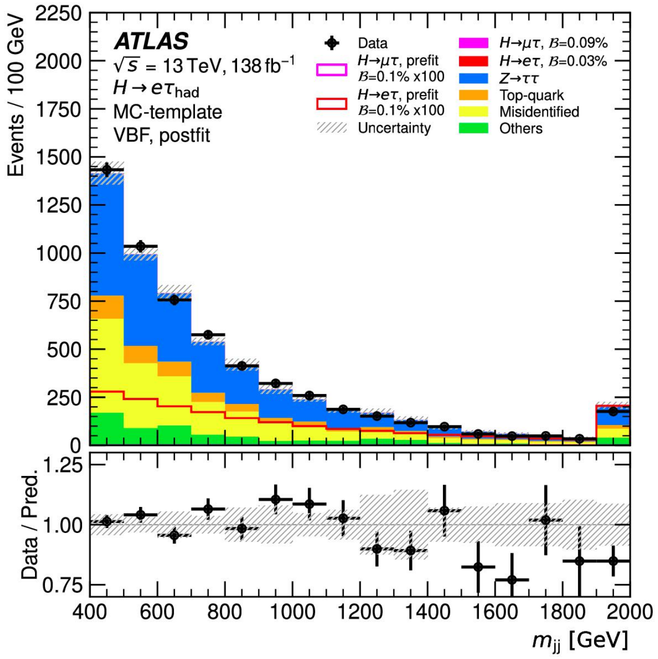


Background estimation with MC-templates

MC-template lephad

- $\boldsymbol{Z \to \tau\tau}$. Different normalization factors (NFs) for VBF and Non VBF. Shared between $e\tau$ and $\mu\tau$ in combined fit.
- **Top-quark**. Shared NFs with MC-template leplep in combined fits.
- $\boldsymbol{Z \to \mu\mu}$. Normalization uncertainty extracted from VR.
- Other minor backgrounds estimated from MC templates.
- **Fakes**. Data-driven fake factor method based on hadronic τ identification.





MVA strategy

- Different MVA strategies for the different analyses, doing separate trainings for VBF and non-VBF to profit from different kinematic properties.
- Two main strategies:

1. **Multiclassifier algorithms based on NNs**. Use signal node as final discriminant.

Symmetry based leplep non-VBF

2. **Multiple classifiers**, each of one devoted to separate the signal from specific backgrounds. Combine the score of each classifier to obtain final discriminant.
   - For example, MC-template leplep uses three BDTs that separate signal from:
     - $Z/H \to \tau\tau + Z \to \ell\ell$.
     - Top-quark + Diboson + $H \to WW$.
     - Misidentified background.

Symmetry based leplep VBF

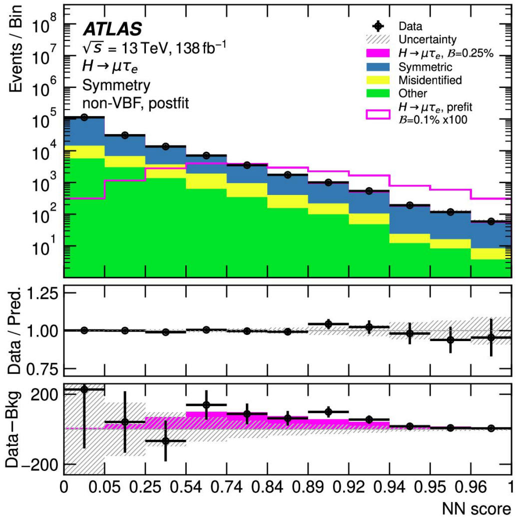
MC-template leplep

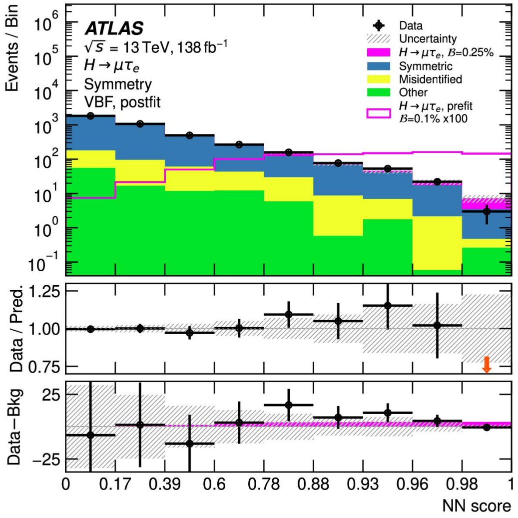
MC-template lephad

MVA output distributions for fit

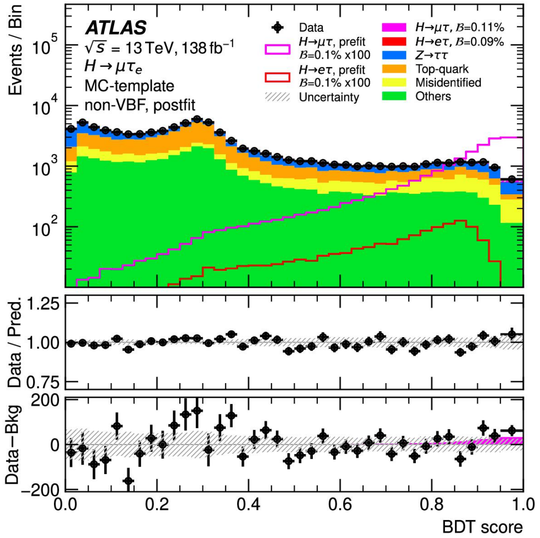
- In this slide, distributions from $\mu\tau$. For MC-template, showing post-fit yields from the combined fit of the MC-template analyses. For Symmetry, post-fit yields from Symmetry standalone fit.

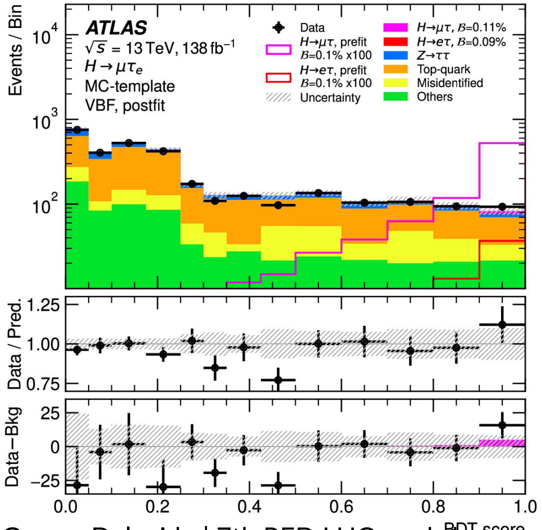
Symm leplep



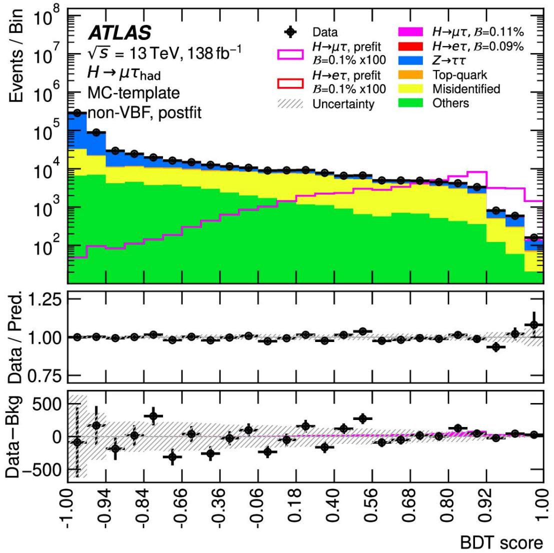


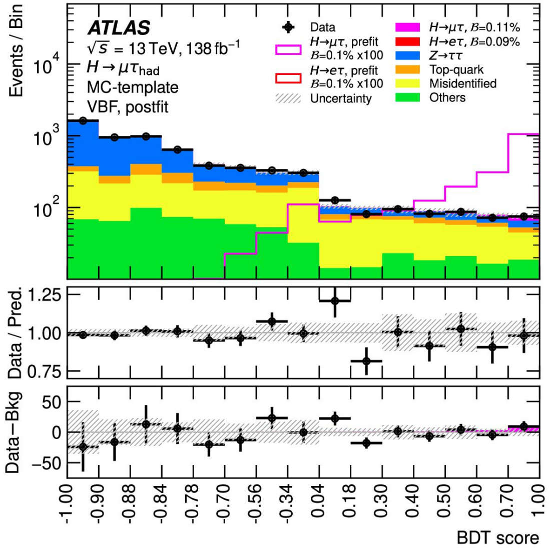
MC leplep





MC lephad





Statistical analysis overview

- Statistical analysis for signal strength $\mu = \mathcal{B}(H \to \ell\tau)$ extraction with **Maximum Binned Likelihood fit** and combining VBF and Non VBF regions. Two signal parametrizations:

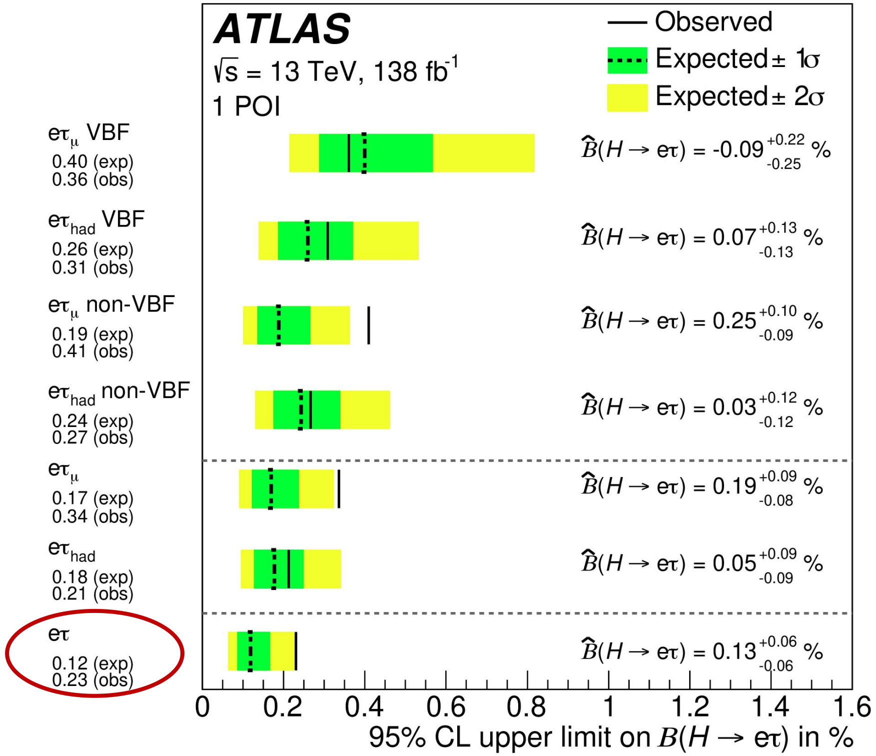
1 POI	Fits in $e\tau$ and $\mu\tau$ channels are independent (e.g. assume $\mathcal{B}(H \to e\tau)$=0 when extracting $\mu = \mathcal{B}(H \to \mu\tau)$)	MC leplep non-VBF + Symm leplep VBF + MC lephad
2 POI	Simultaneous fit of $H \to e\tau$ and $H \to \mu\tau$ signals. 1. No assumption needed on branching ratios. 2. Stronger constraints can be achieved in background nuisance parameters.	MC leplep + MC lephad

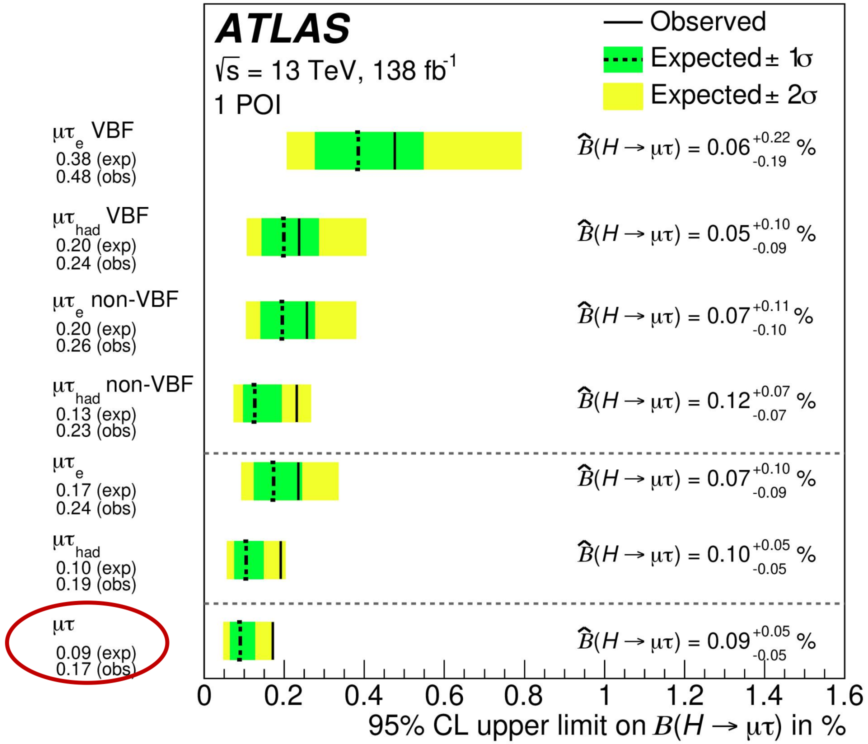
- **1 POI fit scheme** combining three analyses was **chosen based on the sensitivity** of the analyses: Symmetry is used for the leplep VBF categories and MC-template for the leplep non-VBF categories.
- When combining with **Symm. based only 1 POI fit is possible** (one of the channels is required for the background estimate of the other)

1 POI fit

- **Combination** of the **three analyses** with a 1 POI fit setup:
  - **Observed limits** are **above expected ones** for both signals.
  - 2.2σ excess seen for $\mathcal{B}(H \to e\tau)$ and 1.9 σ for $\mathcal{B}(H \to \mu\tau)$.
- 1 POI setup also used to extract **branching ratio difference** with **Symmetry** analysis:

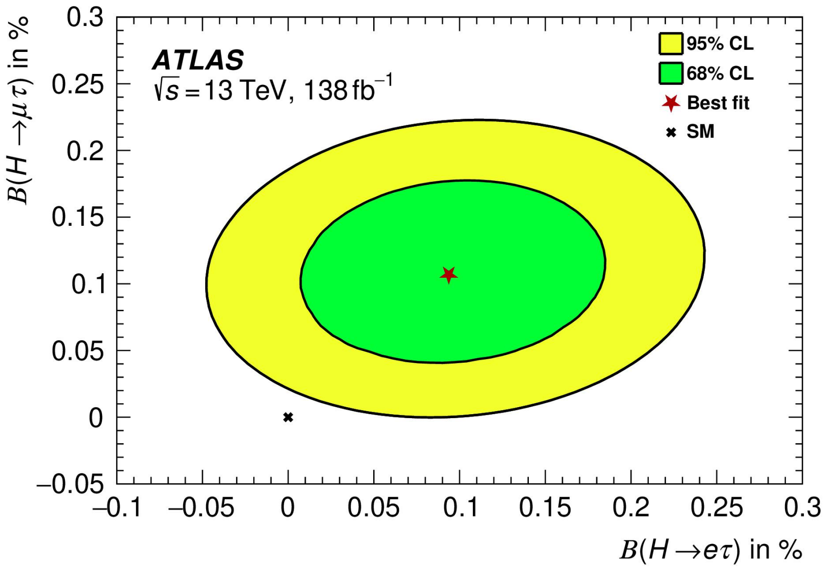
$$\mathcal{B}(H \to \mu\tau) - \mathcal{B}(H \to e\tau) = (0.25 \pm 0.10)\%$$

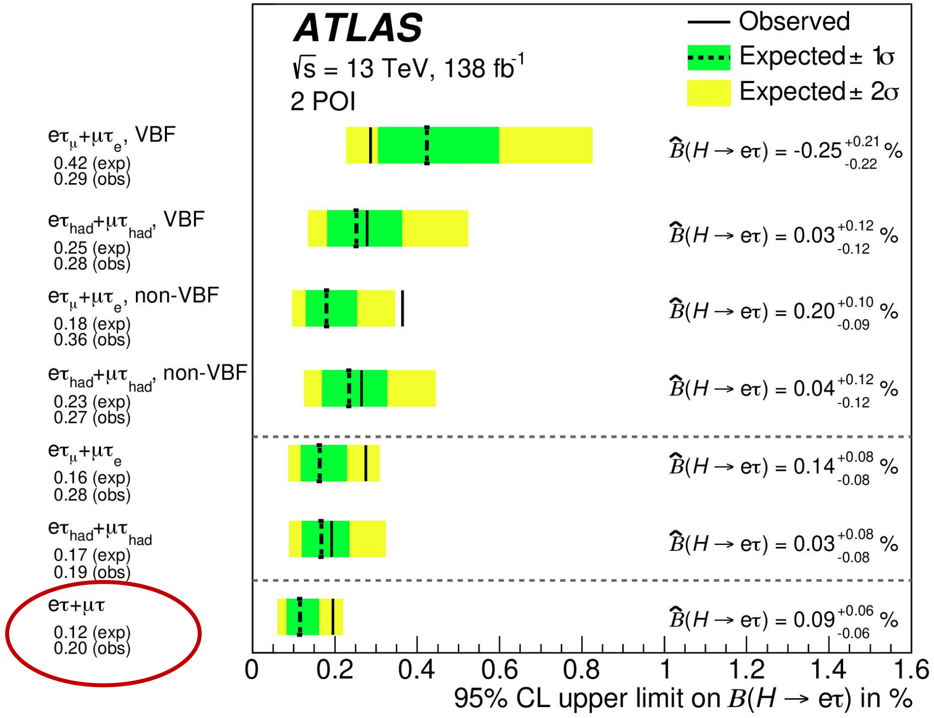


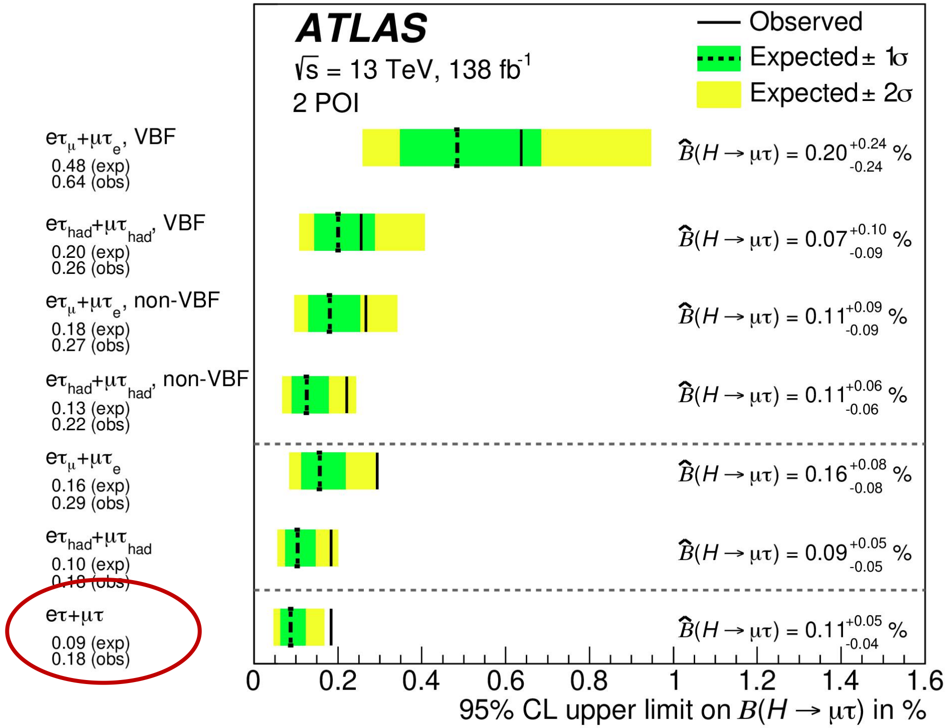


2 POI fit

- **Observed limits** are **above expected ones**, in line with 1 POI fits.
- 1.6σ excess seen for $\mathcal{B}(H \rightarrow e\tau)$ and 2.5σ for $\mathcal{B}(H \rightarrow \mu\tau)$.
  - Not significant. 95% CL limits shown in figures.
- **Global compatibility with SM** within **2.1$\boldsymbol{\sigma}$**.



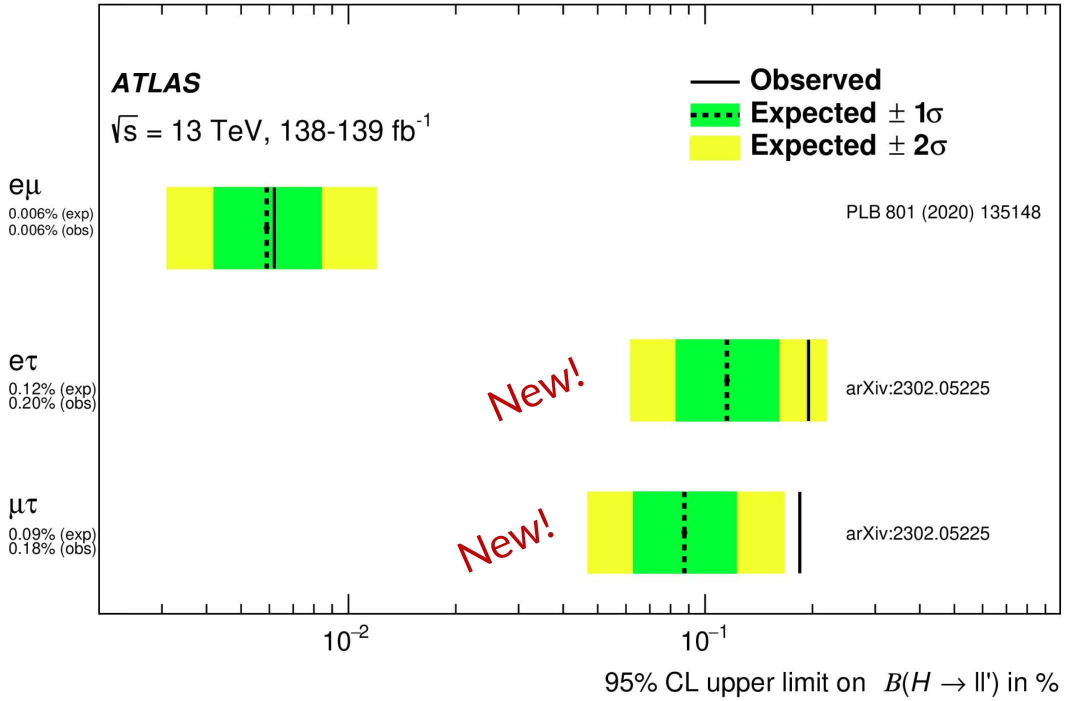




Conclusions

arXiv:2302.05225

- Presented **ATLAS searches** for $\boldsymbol{H \to e\tau}$ and $\boldsymbol{H \to \mu\tau}$ with **138 fb^{-1}.**
- From the simultaneous fit of the two signals, observed (expected) **upper limits at 95% CL** on the branching ratios are 0.20% (0.11%) for $H \to e\tau$ and 0.18% (0.09%) for $H \to \mu\tau$. **Compatibility with SM** within **2.1$\boldsymbol{\sigma}$**.
  - Results complete a full set of ATLAS searches for LFV Higgs boson decays into leptons with the Run 2 dataset.
- Obtained a **branching ratio difference** of $\mathcal{B}(H \to \mu\tau) - \mathcal{B}(H \to e\tau) = (0.25 \pm 0.10)\%$, indicating a **non-significant excess**.
- Prospects of the searches at the HL-LHC have been estimated for the two analysis methods by extrapolating the Run 2 results.



Additional material

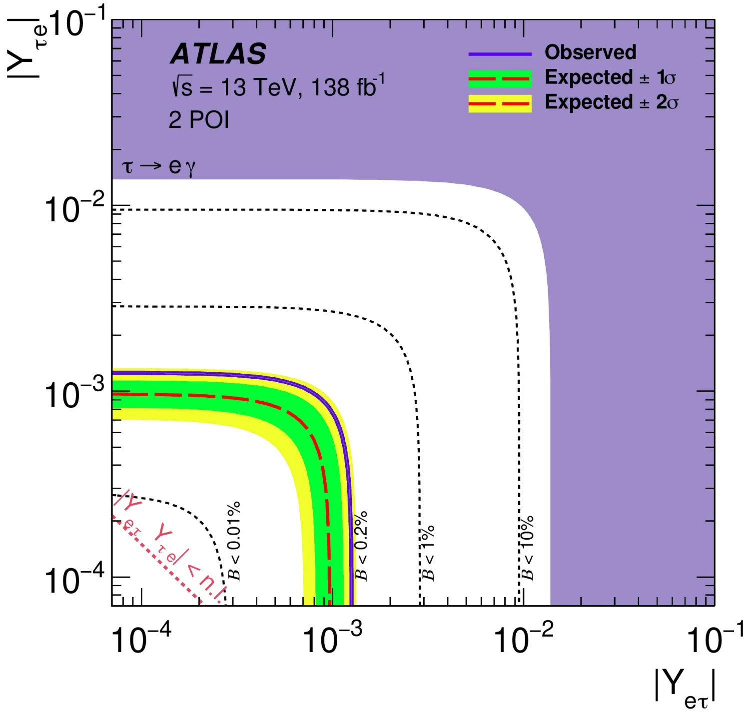
Non-diagonal Yukawa coupling matrix elements

- **Branching ratio** values can be related to **non-diagonal Yukawa coupling** matrix elements:

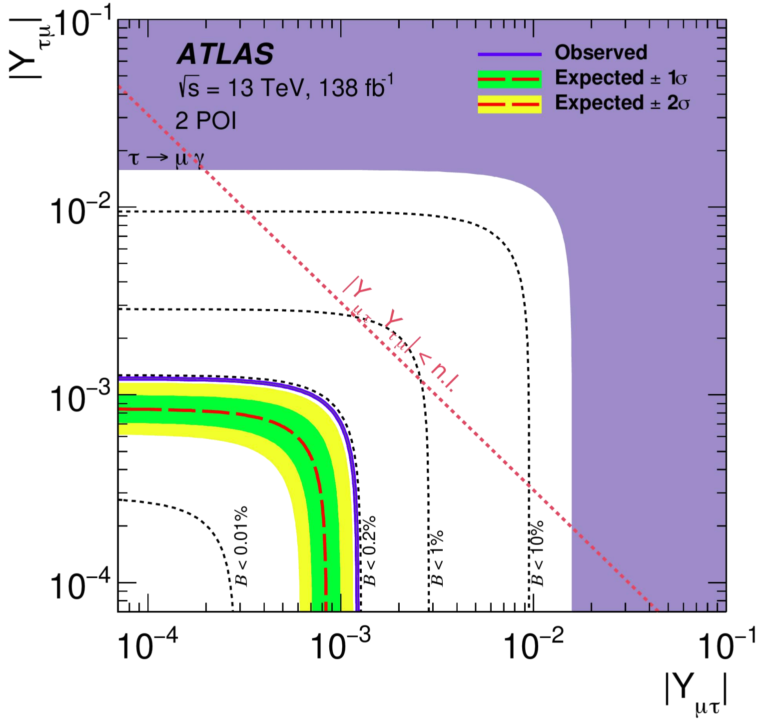
$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H} \frac{\mathcal{B}(H \to \ell\tau)}{1 - \mathcal{B}(H \to \ell\tau)} \Gamma_H^{SM}$$

- For the 2 POI results:

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < \; 0.0012$$



$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\mu\tau}|^2} < \; 0.0012$$



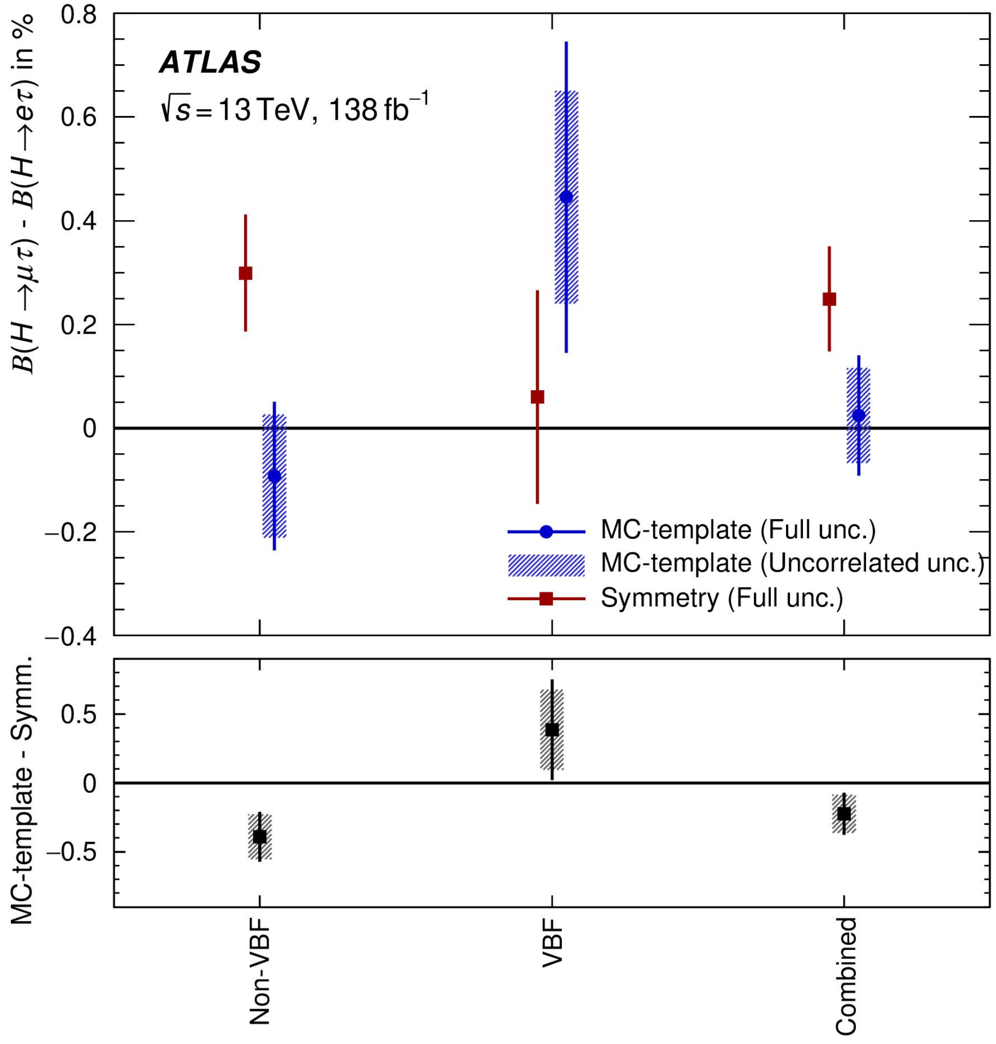
Systematic uncertainties

- Impact of systematic uncertainties similar between the 1 POI and 2 POI fit setups.
- Analysis results **limited** by **systematic uncertainties**. Mainly from:
  - **Background** sample **statistical** uncertainties.
  - **Misidentified bakground** estimation related uncertainties (specially from leplep).

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

Measurement of branching ratio difference

- Symmetry method is **sensitive** to the **difference of branching ratios** $\mathcal{B}(H \to \mu\tau) - \mathcal{B}(H \to e\tau)$.
- Without assumption of one of the $\mathcal{B} = 0$, then the measurement should be interpreted as a branching ratio difference.
- Symmetry results are compared with results from 2 POI fit of the MC-template leplep channel.
- Due to overlap in data, data statistical uncertainties as well as signal uncertainties are correlated between MC-template and Symmetry based analyses.
- Other uncertainties are considered uncorrelated.
- Compatibility found to be within 2.3σ.



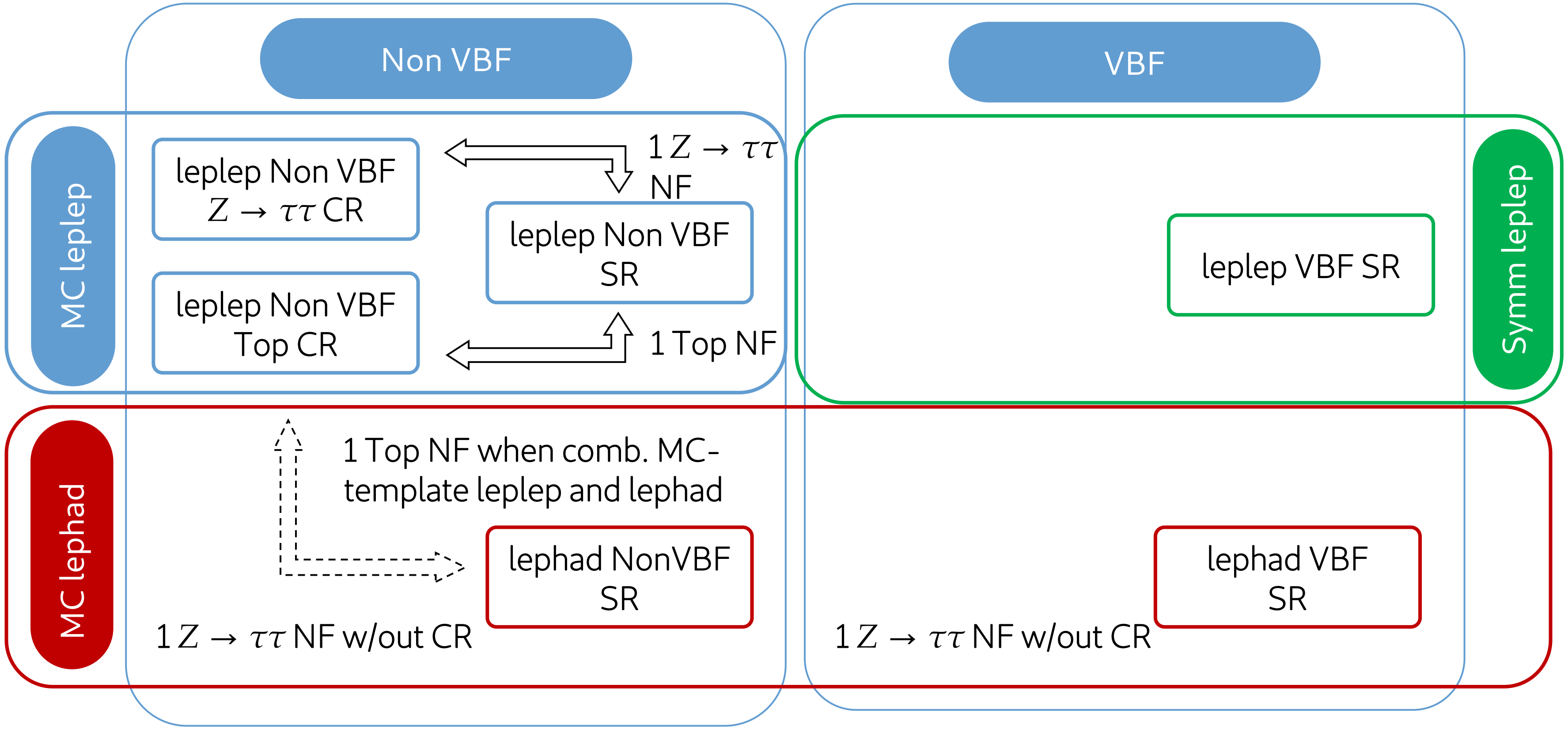
Selection

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

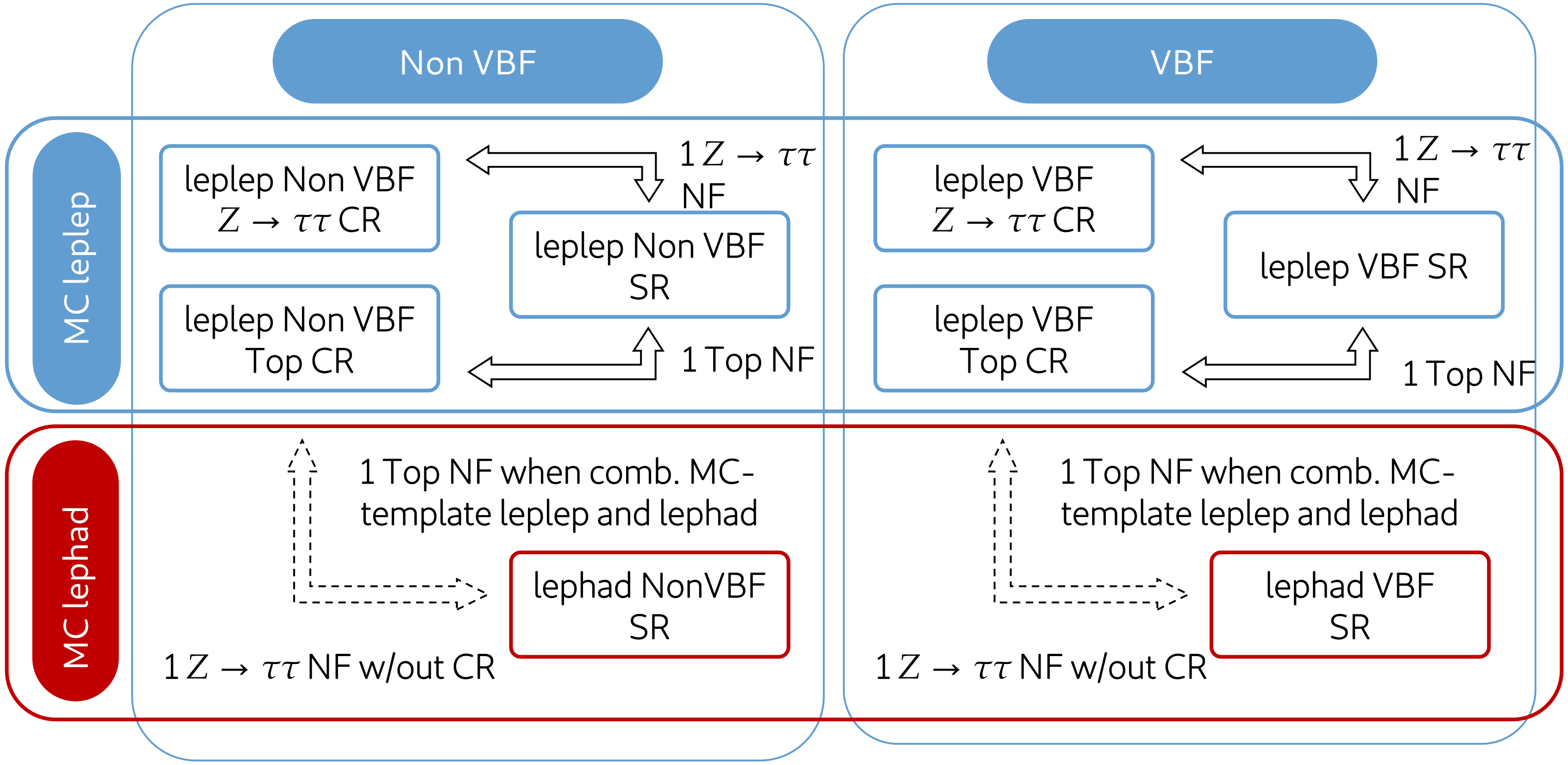
Selection

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
misidentified background CR	*non-VBF* (or *VBF*) category with statistically independent lepton (ℓ or $\tau_{\text{had-vis}}$) selection, see text	
$Z \to \mu\mu$ CR/VR ($\ell\tau_{\ell'}/\ell\tau_{\text{had}}$)	*Baseline* with 35 GeV $< p_{\text{T}}^{\ell_1} <$ 45 GeV 75 GeV $< m_{\ell_1\ell_2} <$ 100 GeV $\lvert\Delta\phi(\ell_2, E_{\text{T}}^{\text{miss}})\rvert < 1.5$ $1.25 < p_{\text{T}}^{\text{track}}(\ell_2)/p_{\text{T}}^{\text{cluster}}(\ell_2) < 3$	*Baseline* $\lvert\eta(\tau)\rvert < 0.1$ 90 GeV $< m_{\text{coll}}(\mu,\tau) <$ 110 GeV
top-quark CR	*non-VBF* (or *VBF*) selection with inverted b-veto requirement	–
$Z \to \tau\tau$ CR	*non-VBF* (or *VBF*) selection with 35 GeV $< p_{\text{T}}^{\ell_1} <$ 45 GeV	–
Diboson VR	*Baseline* $p_{\text{T}}^{\ell_2} >$ 30 GeV 100 GeV $< m_{\ell_1\ell_2} <$ 150 GeV $m_{\text{T}} >$ 30 GeV veto events with jets with $p_{\text{T}} >$ 30 GeV	–

Combined 1 POI fit



Combined 2 POI fit



Fake background estimation

Symm based leplep

Fake estimation

1. Fake Factor method computed in Z+jets CR (2 leptons tagged to Z, 3rd is fake candidate) for $j \to \ell$.
2. $\gamma \to e, \mu \to e$ and $\tau_{\text{had}} \to \ell$ via MC truth info. Maily from $V\gamma, Z \to \mu\mu, Z \to \tau\tau$

Fake factor method

- FF computed in Z+jets CR:

$$FF = \frac{N^{\text{data}}_{(\text{ID,iso})} - N^{\text{promptMC}}_{(\text{ID,iso})}}{N^{\text{data}}_{\text{anti}-(\text{ID,iso})} - N^{\text{promptMC}}_{\text{anti}-(\text{ID,iso})}}$$

- (ID, iso): pass medium id. and isolation
- anti-(ID,iso):
  - For muon: fail iso and pass medium id.
  - For electron: pass loose id. Fail medium id or iso.
- FF binned in lepton flavor, p_{T} and $\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$
- CFs to correct flavour composition differences between SR and CR. Binned in flavour and p_{T}

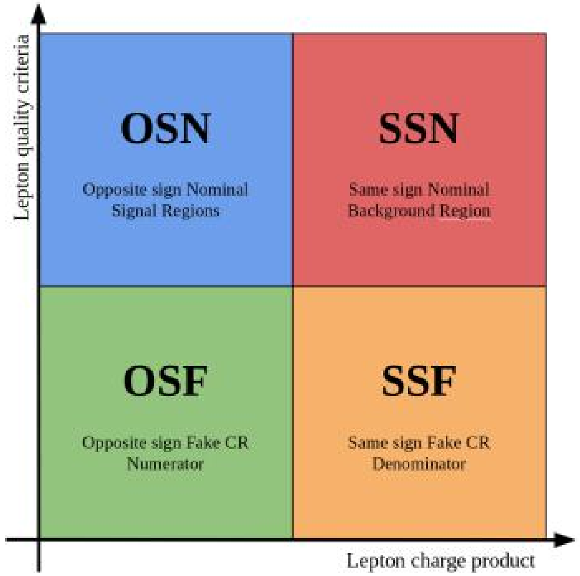
$$CF = \frac{FF^{\text{MC}}_{\text{SR}}}{FF^{\text{MC}}_{\text{Z+jets}}} \quad N^{\text{fakes}}_{\text{SR}} = FF \times CF \times (N^{\text{data}}_{\text{SR; anti}-(\text{ID,iso})} - N^{\text{promptMC}}_{\text{SR, anti}-(\text{ID,iso})})$$

Fake background estimation

MC-template leplep

ABCD method

- OSN: SR. SSN: SR sselection but SS charges of light leptons.
- OSF and SSF. Fake enriched regions (Fake CRs). anti-ID and anti-iso + other lepton quality criteria:
  - For muon: fail iso and pass medium id.
  - For electron: either fail isolation or medium id. but pass loose id.
- Assume $\mathrm{OSN} = \mathrm{SSN} \times \frac{\mathrm{OSF}}{\mathrm{SSF}} = \mathrm{SSN} \times \mathrm{TF}$
- Transfer factor parametrized in terms of trigger and b-veto/tag



Fake background estimation

MC-template lephad

- Estimate of $j \to \tau_{\text{had}}$ with W+jets and QCD multijets as main sources (two dedicated CRs). Data-driven fake factor method.

Fake Factor Method

- $N^{\text{SR}}_{\text{fakes}} = (N^{\text{anti}-\tau}_{\text{data}} - N^{\text{anti}-\tau}_{\text{MC, no } j\to\tau}) \times \mathcal{F}$
- $\textbf{anti} - \tau$: pass VeryLoose ID but fail Tight ID
- Two main sources: QCD multijets and W+jets.Two dedicated CRs.

$$\mathcal{F} = R_{QCD}F_{QCD} + (1 - R_{QCD})F_W$$

- Derive FF for each source and apply to $\textbf{anti} - \tau$ events in SR

$$F_i = \frac{N^{\text{CR}_\text{i}}_{\text{data}} - N^{\text{CR}_\text{i}}_{\text{MC, no } j\to\tau}}{N^{\text{anti}-\tau,\,\text{CR}_\text{i}}_{\text{data}} - N^{\text{anti}-\tau,\,\text{CR}_\text{i}}_{\text{MC, no } j\to\tau}}$$

- FF bined in p_{T} and 1/3 prong.

MVA strategy

Symmetry based leplep

NNs trained with Keras

Separate training for Non VBF and VBF. Shared between $e\tau_\mu$ and $\mu\tau_e$

Non VBF

1 Multiclassifier NN with 3 output nodes. Signal output node used for fit.

VBF

3 BDTs. Scores combined linearly.

- LFV vs. $Z\tau\tau$+$H\tau\tau$+MCfakes
- LFV vs. Top+VV+HWW
- LFV vs. Fakes

MC-template leplep

BDTs with TMVA

Separate training for Non VBF and VBF. Shared between $e\tau_\mu$ and $\mu\tau_e$

Non VBF and VBF

3 BDTs. Scores combined linearly.

- LFV vs. $Z\tau\tau$+$H\tau\tau$+$Z\ell\ell$
- LFV vs. Top+VV+HWW
- LFV vs. Fakes

MC-template lephad

BDTs with TMVA

Separate trainings for Non VBF and VBF and for $e\tau_\mu$, $\mu\tau_e$

Non VBF $e\tau$

3 BDTs. Scores combined linearly.

- LFV vs. $Z\tau\tau$
- LFV vs. Fakes
- LFV vs. Other backgrounds

Non VBF $\mu\tau$ and VBF

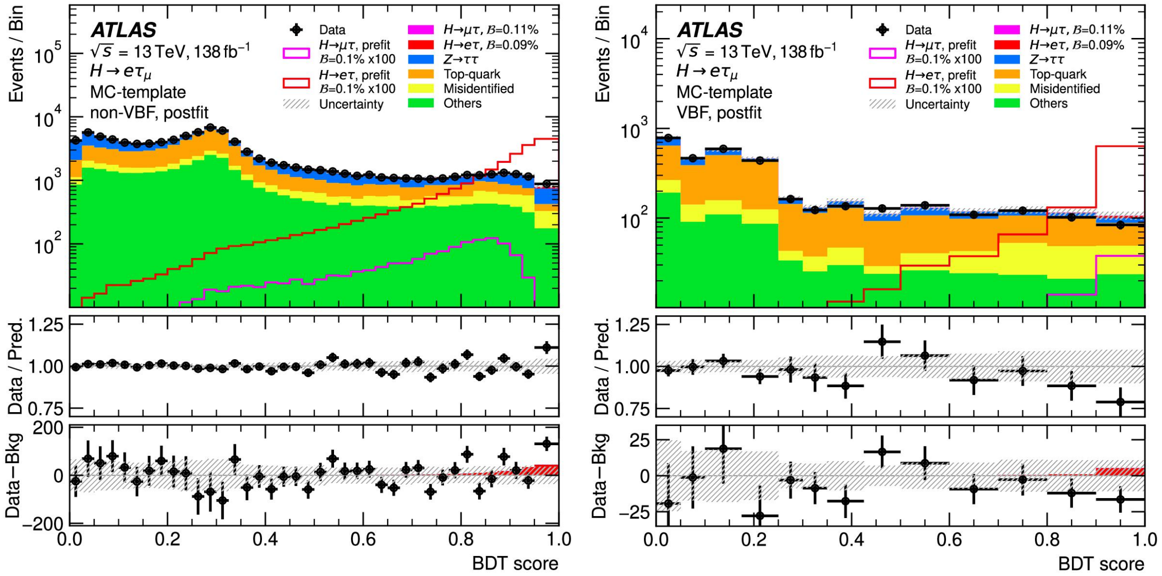
2 BDTs. Scores combined linearly (NonVBF $\mu\tau$) or quadratically (VBF).

- LFV vs. $Z\tau\tau$
- LFV vs. Other backgrounds

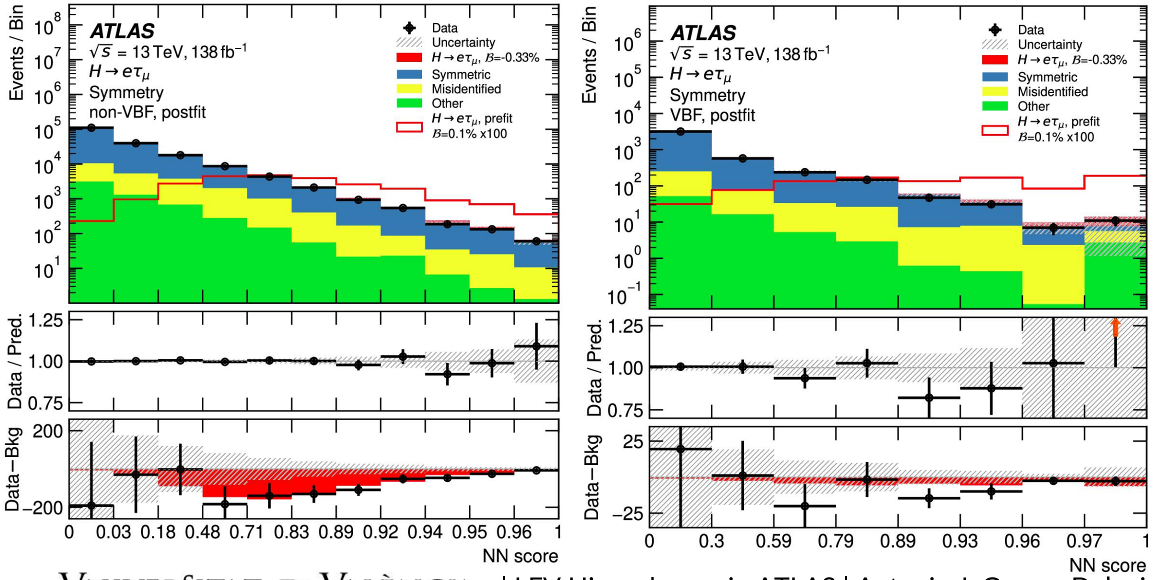
MVA output distributions for fit

- In this slide, distributions from $e\tau$.
- For MC-template, postfit signal contributions from the 2 POI fit.
- For Symmetry, postfit signals coming from 1POI Symmetry standalone fit.

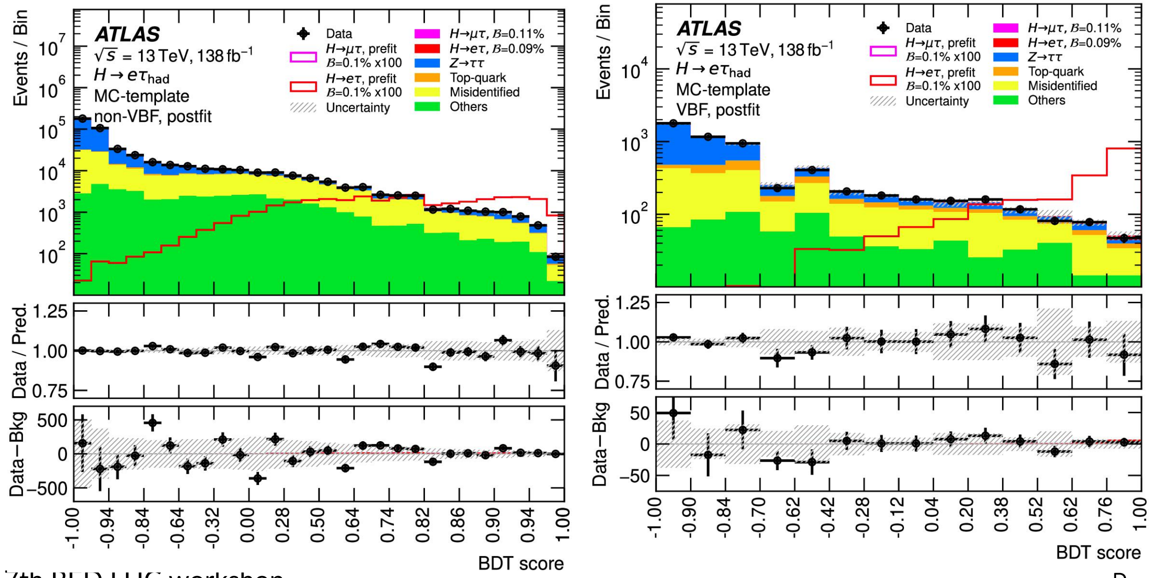
MC leplep



Symm leplep

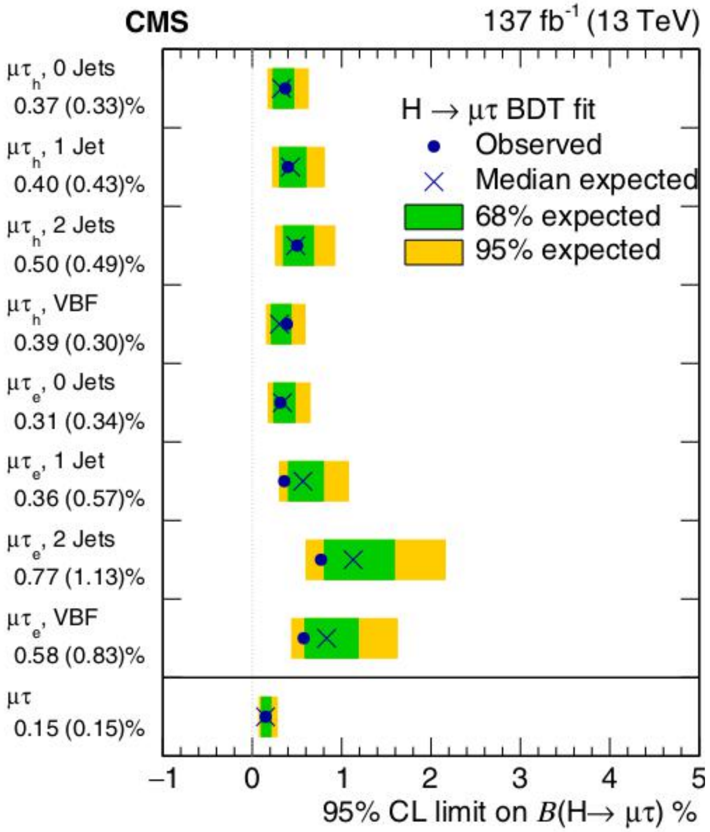


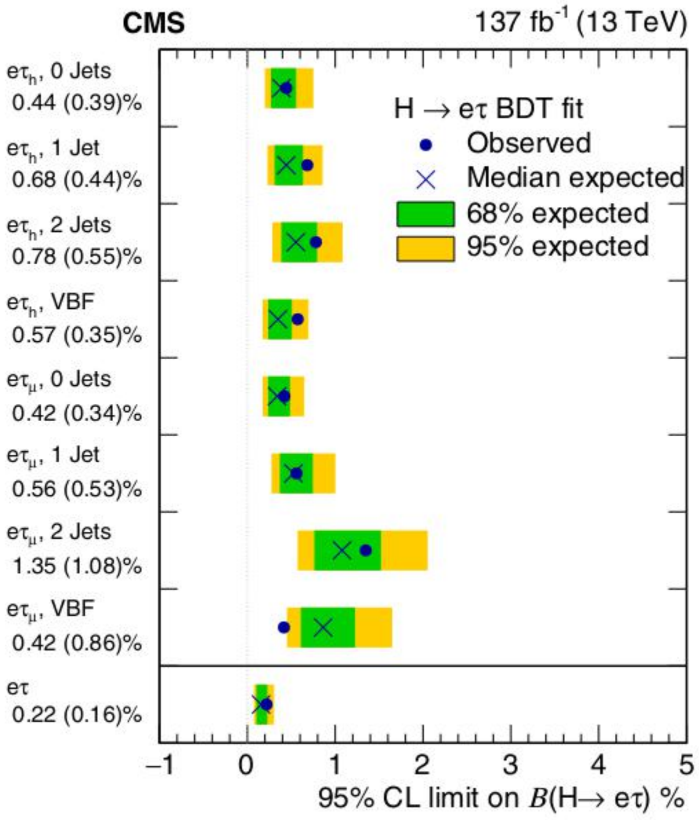
MC lephad



Comparison with CMS

- Main differences with respect to ATLAS search:
  - **Leplep** background estimation is **MC-template**.
  - Using **embedding** for $Z \rightarrow \tau\tau$.
  - **New TauID** based on DNN (70% eff, 1% mis-id).
  - **1 POI** fit for branching ratio extraction.
  - **Lepton assignment** based on p_T ordering in lab frame.
  - MVA based on **BDT**. Trained only with part of the background.
  - **Finer categorization** of Non VBF regions depending on number of jets.





CMS 137 fb^{-1} [2105.03007]

Combined 1 POI fit

1 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	0.6	0.4
Misidentified background ($\ell\tau_{\text{had}}$)	2.1	1.5
Misidentified background ($\ell\tau_{\ell'}$)	2.9	1.6
Jet and $E_{\text{T}}^{\text{miss}}$	1.1	1.1
Electrons and muons	0.2	0.5
Luminosity	0.6	0.5
Hadronic τ decays	0.9	1.0
Theory (signal)	0.9	0.7
Theory (Z + jets processes)	1.0	1.2
Theory (top-quark processes)	0.3	0.3
Theory (diboson processes)	0.4	0.7
$Z \to \ell\ell$ normalisation	0.2	0.7
Symmetric background estimate	0.2	0.1
Background sample size	4.2	2.4
Total systematic uncertainty	5.3	3.9
Data sample size	2.9	2.7
Total	6.1	4.7