Searches of Lepton-Flavour-Violating Decays of the Higgs Boson with the ATLAS Detector at the HL-LHC

based on ATL-PHYS-PUB-2022-054

New Frontiers in Lepton Flavour, Pisa 2023

Naman Kumar Bhalla
on behalf of the ATLAS Collaboration

Physikalisches Institut, Albert-Ludwigs-Universität Freiburg

Monday 15th May, 2023

Masse und Symmetrien nach der
GRK 2044
Entdeckung des Higgs-Teilchens am LHC

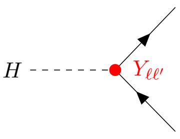
ATLAS
EXPERIMENT

FSP ATLAS
Erforschung von
Universum und Materie

UNI
FREIBURG

Lepton Flavour Violation (LFV)

- Lepton flavour → accidental symmetry of the SM ($Y_{\ell\ell'} \propto \delta_{\ell\ell'}$)
- Violation observed in nature → neutrino oscillations
  - ⇒ Motivates searches for LFV involving charged leptons (cLFV)
- LFV decays of the Higgs boson predicted by various extensions of the SM
- Search for independent signals:
  - $H \to e\tau$
  - $H \to \mu\tau$
  - ⇒ Limits on $H \to e\mu$ already too strong
- Obtain expected sensitivities at HL-LHC
  - Extrapolated from Run 2* arXiv:2302.05225
- Two channels: $H \to \ell\tau_{\text{had}}$ and $H \to \ell\tau_{\ell'}$
- Two methods for background estimation:
  - MC-template method
  - Symmetry method



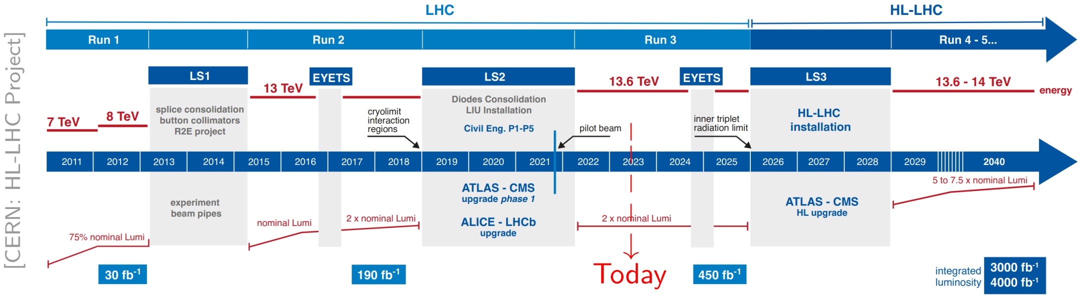
Most stringent limits on $\mathcal{B}(H \to \ell\ell')$

Decay	95% C.L. upper limit	
$H \to e\mu$	$0.0044\,\%$	[CMS-PAS-HIG-22-002]
$H \to e\tau$	$0.20\,\%$	[arXiv:2302.05225]
$H \to \mu\tau$	$0.15\,\%$	[Phys. Rev. D 104 (2021) 032013]

---

*See Antonio's talk for details on Run 2 analysis

High Luminosity LHC (HL-LHC)



- Upgrade the LHC for 5 to 7.5 times nominal instantaneous luminosity
- Integrated luminosity ≈ 20 times higher than Run 2
- Allows more accurate measurements of new particles and observations of rarer processes
- Upgrade detectors to cope with high collision and pileup rates
- Physics runs scheduled to start in 2029 with higher beam energy

Extrapolation to HL-LHC

- Scale Run 2 measurement inputs
  - ⇒ Inputs for HL-LHC fits
- Correct for following effects:
  - Larger integrated luminosity
  - Higher center-of-mass energy
  - Reduced uncertainties:
    - ⇒ Higher statistical precision
    - ⇒ Upgrades of the detector
    - ⇒ More precise theory calculations

Extrapolation to HL-LHC

- Scale Run 2 measurement inputs
  - ⇒ Inputs for HL-LHC fits
- Correct for following effects:
  - Larger integrated luminosity
  - Higher center-of-mass energy
  - Reduced uncertainties:
    - ⇒ Higher statistical precision
    - ⇒ Upgrades of the detector
    - ⇒ More precise theory calculations

Integrated Luminosity

$$\mathrm{SF}_{\mathcal{L}_{\text{int}}} = \frac{\mathcal{L}_{\text{int}}(\text{HL-LHC})}{\mathcal{L}_{\text{int}}(\text{Run 2})} = \frac{3000\,\text{fb}^{-1}}{138.4\,\text{fb}^{-1}} = 21.68$$

Extrapolation to HL-LHC

- Scale Run 2 measurement inputs
  - ⇒ Inputs for HL-LHC fits
- Correct for following effects:
  - Larger integrated luminosity
  - Higher center-of-mass energy
  - Reduced uncertainties:
    - ⇒ Higher statistical precision
    - ⇒ Upgrades of the detector
    - ⇒ More precise theory calculations

Integrated Luminosity

$$\mathsf{SF}_{\mathcal{L}_{\mathsf{int}}} = \frac{\mathcal{L}_{\mathsf{int}}(\mathsf{HL\text{-}LHC})}{\mathcal{L}_{\mathsf{int}}(\mathsf{Run\ 2})} = \frac{3000\,\mathrm{fb}^{-1}}{138.4\,\mathrm{fb}^{-1}} = 21.68$$

Center-of-Mass Energy

$$\mathsf{SF}_{\sqrt{s}} = \frac{\sigma(14\,\mathrm{TeV})}{\sigma(13\,\mathrm{TeV})} \in [1.10, 1.21]$$

Extrapolation to HL-LHC

- Scale Run 2 measurement inputs
  - ⇒ Inputs for HL-LHC fits
- Correct for following effects:
  - Larger integrated luminosity
  - Higher center-of-mass energy
  - Reduced uncertainties:
    - ⇒ Higher statistical precision
    - ⇒ Upgrades of the detector
    - ⇒ More precise theory calculations

Center-of-Mass Energy

$$\mathsf{SF}_{\sqrt{s}} = \frac{\sigma(14\,\mathrm{TeV})}{\sigma(13\,\mathrm{TeV})} \in [1.10, 1.21]$$

Integrated Luminosity

$$\mathsf{SF}_{\mathcal{L}_{\mathsf{int}}} = \frac{\mathcal{L}_{\mathsf{int}}(\mathsf{HL\text{-}LHC})}{\mathcal{L}_{\mathsf{int}}(\mathsf{Run\ 2})} = \frac{3000\,\mathrm{fb}^{-1}}{138.4\,\mathrm{fb}^{-1}} = 21.68$$

Uncertainties

- Stat. unc. on data-driven prediction

$$\mathsf{SF}^{\mathsf{DataDriven}}_{\mathsf{StatUnc}} = 1/\sqrt{\mathsf{SF}_{\mathcal{L}_{\mathsf{int}}}} = 0.21$$

- Stat. unc. on MC prediction (two cases)

$$\mathsf{SF}^{\mathsf{MC,\ Nom.}}_{\mathsf{StatUnc}} = 0, \quad \mathsf{SF}^{\mathsf{MC,\ Alt.}}_{\mathsf{StatUnc}} = 0.21$$

- Scale systematics for predicted detector upgrades and theory precision ($\mathsf{SF}_{\mathsf{Syst}}$)

Expected Improvements in Systematic Uncertainties

- Experimental uncertainties affected by
  - Harsher experimental conditions
  - Upgrades in detector
  - Better object reconstruction

  ⇒ Expect $E_{\mathrm{T}}^{\mathrm{miss}}$ and flavour tagging unc. to improve
- Stat.-related unc. on $\tau_{\text{had-vis}}$

  ⇒ Expected to be negligible
- Stat.-related unc. on data-driven estimates

  ⇒ Scaled by $\mathrm{SF}_{\mathrm{StatUnc}}^{\mathrm{DataDriven}} = 0.21$
- Higher precision in theory calculations predicted[†]
- Assume $1.0\,\%$ uncertainty on luminosity

  ⇒ $1.7\,\%$ in the Run 2 analysis

Uncertainties	$\mathrm{SF}_{\mathrm{Syst}}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.50
Flavour tagging c- and b-jets	0.50
Jet, others	1.00
Electron and muon	1.00
$\tau_{\text{had-vis}}$ ID, stat.-related	0.00
$\tau_{\text{had-vis}}$, others	1.00
Data-driven estimates, stat.-related	0.21
Data-driven estimates, others	1.00
Bkg. modelling, PDF	0.40
Sig. modelling, PDF	[0.41, 0.46]
Modelling, others	0.50
Luminosity	0.59

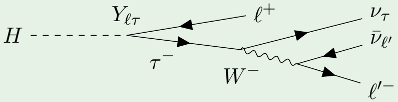
Abstracted from [ATL-PHYS-PUB-2022-054]

[†] [Eur. Phys. J. C 78 (2018) 962]

MC-Template Method

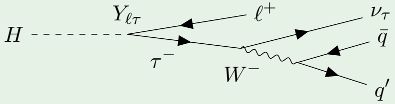
$H \to \ell\tau_{\ell'}$ Channel

$$H \to \ell\tau \to \boldsymbol{\ell\ell' 2\nu} \quad \ell, \ell' \in e, \mu$$



$H \to \ell\tau_{\text{had}}$ Channel

$$H \to \ell\tau \to \boldsymbol{\ell\nu} + \textbf{hadrons} \quad \ell \in e, \mu$$



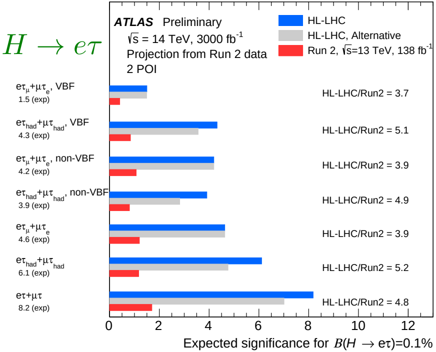
- Most backgrounds estimated via MC templates
- 4 regions per search: $(\tau_{\ell'},\ \tau_{\text{had}}) \times$ (VBF, non-VBF)
- Final discriminant: Boosted Decision Tree score
- Perform profile likelihood fits with scaled inputs
  - ⇒ Simultaneously for 2 POI: $\mathcal{B}(H \to e\tau)$ and $\mathcal{B}(H \to \mu\tau)$
  - ⇒ Using Asimov data set $= \sum$ weighted backgrounds
- Obtain expected significances for $\mathcal{B}(H \to \ell\tau) = 0.1\,\%$ at HL-LHC

MC-Template Method Sensitivity

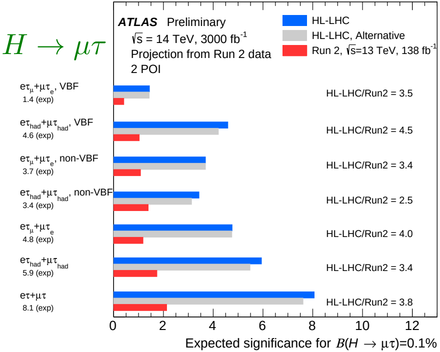
- Compare sensitivity for $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ signal at HL-LHC

Significance for $\mathcal{B} = 0.1\,\%$

$H \rightarrow e\tau$



$H \rightarrow \mu\tau$



[ATL-PHYS-PUB-2022-054]

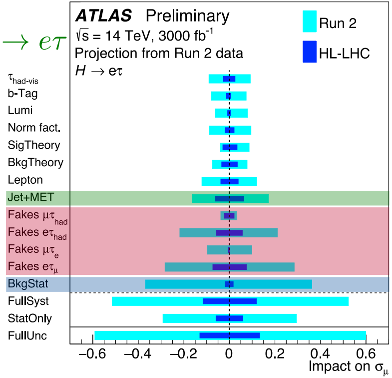
- Expected significance $> 8\sigma$ at HL-LHC for $\mathcal{B}(H \rightarrow \ell\tau) = 0.1\,\%$
  - VBF category of $\ell\tau_{\text{had}}$ most sensitive with largest improvements
  - VBF (non-VBF) category dominant in $\ell\tau_{\text{had}}$ ($\ell\tau_{\ell'}$) channel
- Alternative case with $\text{SF}^{\text{MC, Alt.}}_{\text{StatUnc}} = 0.21$ worse by $15\,\%$ $(5\,\%)$ for $H \rightarrow e\tau$ $(H \rightarrow \mu\tau)$

Impact of Uncertainties with MC-Template Method

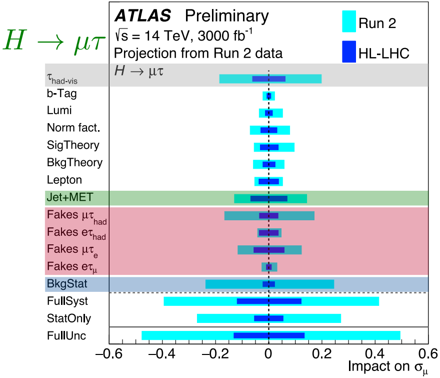
- Compare impact of uncertainties on σ_μ between Run 2 and HL-LHC scenarios

σ_μ: Unc. on signal strength

$H \rightarrow e\tau$



$H \rightarrow \mu\tau$



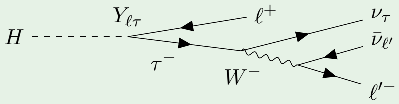
[ATL-PHYS-PUB-2022-054]

- Dominated by systematic uncertainties in both scenarios
  - Leading contributors at HL-LHC: *Jet* $+ E_{\mathrm{T}}^{\mathrm{miss}}$ and *Fakes* uncertainties
  - Significant contributions from uncertainties on $\tau_{\text{had-vis}}$ in $H \rightarrow \mu\tau$
- Stat. unc. on background prediction (*BkgStat*) strongly reduced at HL-LHC

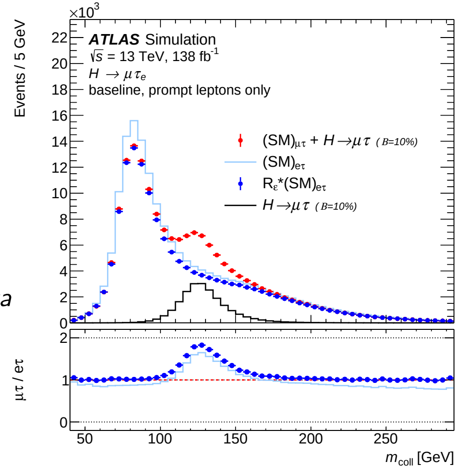
Symmetry Method

$H \to \ell\tau_{\ell'}$ Channel

$$H \to \ell\tau \to \ell\ell' 2\nu \quad \ell, \ell' \in e, \mu$$



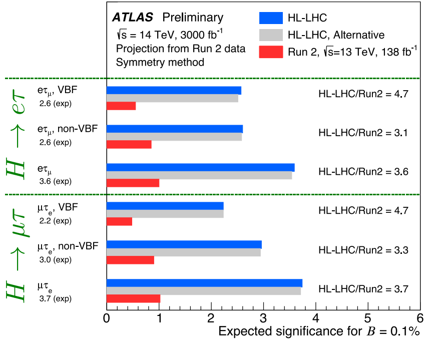
- ▶ Data-driven approach for most backgrounds
  - $\Rightarrow$ $e\tau_\mu$ acts as background for $\mu\tau_e$ and *vice-versa*
- ▶ Currently only includes $\ell\tau_{\ell'}$ channel
- ▶ 2 regions per search: VBF and non-VBF
- ▶ Final discriminant: Neural Network score
- ▶ Directly sensitive to $\Delta\mathcal{B}(H \to \ell\tau_{\ell'})$
  - $\Rightarrow$ $H \to e\tau$ and $H \to \mu\tau$ anti-correlated $\Rightarrow$ Perform 1 POI fits assuming other $\mathcal{B} = 0$
- ▶ Obtain expected significances for $\mathcal{B}(H \to \ell\tau) = 0.1\,\%$ from profile likelihood fits



[arXiv:2302.05225] (Auxiliary Material)

Symmetry Method Sensitivity

- Compare sensitivity for $H \to e\tau$ and $H \to \mu\tau$ signal at HL-LHC



Significance for $\mathcal{B} = 0.1\,\%$

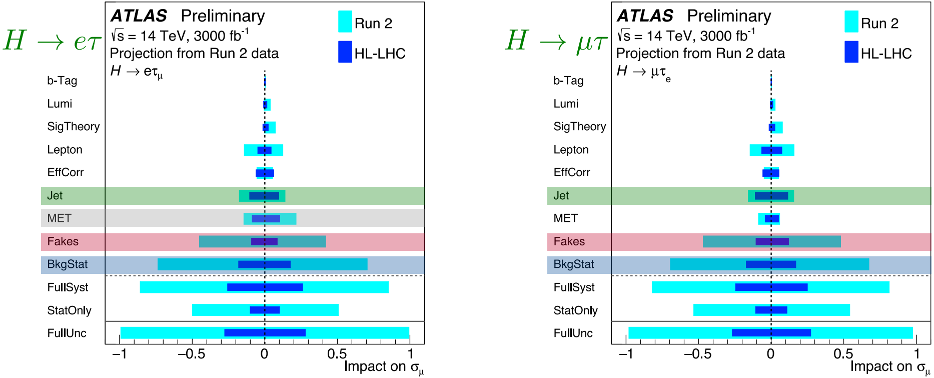
[ATL-PHYS-PUB-2022-054]

- Expected significance $> 3.5\sigma$ at HL-LHC for $\mathcal{B}(H \to \ell\tau) = 0.1\,\%$
  - Largest improvements in VBF category → statistically limited in Run 2
  - Both categories competitive for $e\tau_{\mu}$, but non-VBF better for $\mu\tau_{e}$
- Alternative case with $\mathrm{SF}^{\text{MC, Alt.}}_{\text{StatUnc}} = 0.21$ worse by only $1.5\,\%$ for both signals

Impact of Uncertainties with Symmetry Method

- Compare impact of uncertainties on σ_μ between Run 2 and HL-LHC scenarios

σ_μ: Unc. on signal strength



[ATL-PHYS-PUB-2022-054]

- Dominated by systematic uncertainties in both scenarios
  - Leading contributor: Stat. unc. on background prediction (*BkgStat*)

    ⇒ Data-driven method → indirectly dominated by statistical uncertainties in data
- Other significant contributors: $E_\mathrm{T}^\mathrm{miss}$ (only in $H \to e\tau$), *Fakes* and *Jet* uncertainties

Sensitivity Comparison of Methods ($H \to \ell\tau_{\ell'}$)

- Compare sensitivities of the two background estimation methods
  - ⇒ Performed in $H \to \ell\tau_{\ell'}$ channel only

Significance for $\mathcal{B} = 0.1\ \%$

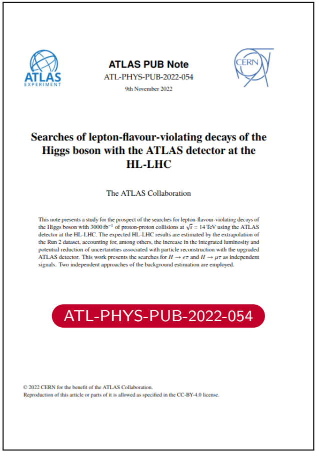
	Case	Symmetry method				MC-template method			
		$e\tau_\mu$		$\mu\tau_e$		$e\tau_\mu$		$\mu\tau_e$	
		Value	Ratio	Value	Ratio	Value	Ratio	Value	Ratio
Run 2	VBF	0.55		0.48		0.41		0.41	
	Non-VBF	0.85		0.90		1.07		1.08	
	Combined	1.00		1.02		1.20		1.18	
HL-LHC	VBF	2.57	4.67	2.23	4.65	1.50	3.66	1.44	3.51
	Non-VBF	2.60	3.06	2.96	3.29	4.19	3.92	3.69	3.42
	Combined	3.59	3.59	3.74	3.67	4.63	3.86	4.76	4.03

[ATL-PHYS-PUB-2022-054]

- Even at HL-LHC MC-template (Symmetry) method dominated by systematic (stat.) unc.
- With the current extrapolation
  - MC-template method shows slight advantage with both regions combined
    - ⇒ Sensitivity driven by the non-VBF region in $\ell\tau_{\ell'}$ channel
  - Symmetry method expected to perform better in the VBF region
- In reality it will depend on how systematic and statistical uncertainties evolve

Conclusion

- Study sensitivity for LFV decays of Higgs boson at HL-LHC
  - Extrapolated from Run 2 measurements arXiv:2302.05225
- Two independent methods for background estimation
  - MC-template method: Both $\ell\tau_{\text{had}}$ and $\ell\tau_{\ell'}$ channels
    - $\Rightarrow$ Expected $Z > 8\sigma$ at HL-LHC for $\mathcal{B}(H \to \ell\tau) = 0.1\,\%$
    - $\Rightarrow$ Dominated by systematic uncertainties
  - Symmetry method: Only $\ell\tau_{\ell'}$ channel (for now)
    - $\Rightarrow$ Expected $Z > 3.5\sigma$ at HL-LHC for $\mathcal{B}(H \to \ell\tau) = 0.1\,\%$
    - $\Rightarrow$ Indirectly dominated by statistical uncertainties
  - $\rightarrow$ Would have to see how different uncertainties evolve
- Improvements in methods could further augment sensitivities



ATLAS PUB Note
ATL-PHYS-PUB-2022-054
9th November 2022

Searches of lepton-flavour-violating decays of the Higgs boson with the ATLAS detector at the HL-LHC

The ATLAS Collaboration

This note presents a study for the prospect of the searches for lepton-flavour-violating decays of the Higgs boson with 3000 fb^{-1} of proton-proton collisions at $\sqrt{s} = 14$ TeV using the ATLAS detector at the HL-LHC. The expected HL-LHC results are estimated by the extrapolation of the Run 2 dataset, accounting for, among others, the increase in the integrated luminosity and potential reduction of uncertainties associated with particle reconstruction with the upgraded ATLAS detector. This work presents the searches for $H \to e\tau$ and $H \to \mu\tau$ as independent signals. Two independent approaches of the background estimation are employed.

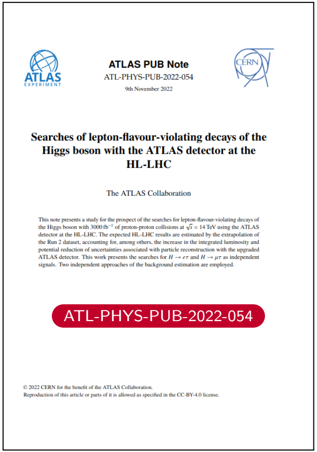
ATL-PHYS-PUB-2022-054

© 2022 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.

Conclusion

- Study sensitivity for LFV decays of Higgs boson at HL-LHC
  - Extrapolated from Run 2 measurements arXiv:2302.05225
- Two independent methods for background estimation
  - MC-template method: Both $\ell\tau_{\text{had}}$ and $\ell\tau_{\ell'}$ channels
    - ⇒ Expected $Z > 8\sigma$ at HL-LHC for $\mathcal{B}(H \to \ell\tau) = 0.1\,\%$
    - ⇒ Dominated by systematic uncertainties
  - Symmetry method: Only $\ell\tau_{\ell'}$ channel (for now)
    - ⇒ Expected $Z > 3.5\sigma$ at HL-LHC for $\mathcal{B}(H \to \ell\tau) = 0.1\,\%$
    - ⇒ Indirectly dominated by statistical uncertainties

  → Would have to see how different uncertainties evolve
- Improvements in methods could further augment sensitivities



ATLAS PUB Note
ATL-PHYS-PUB-2022-054
9th November 2022

Searches of lepton-flavour-violating decays of the Higgs boson with the ATLAS detector at the HL-LHC

The ATLAS Collaboration

This note presents a study for the prospect of the searches for lepton-flavour-violating decays of the Higgs boson with 3000 fb^{-1} of proton-proton collisions at $\sqrt{s} = 14$ TeV using the ATLAS detector at the HL-LHC. The expected HL-LHC results are estimated by the extrapolation of the Run 2 dataset, accounting for, among others, the increase in the integrated luminosity and potential reduction of uncertainties associated with particle reconstruction with the upgraded ATLAS detector. This work presents the searches for $H \to e\tau$ and $H \to \mu\tau$ as independent signals. Two independent approaches of the background estimation are employed.

ATL-PHYS-PUB-2022-054

© 2022 CERN for the benefit of the ATLAS Collaboration.
Reproduction of this article or parts of it is allowed as specified in the CC-BY-4.0 license.

Thank You!!

Backup

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

[arXiv:2302.05225]

Scale Factors for Center-of-Mass Energy

Sample	Scale factor for $\sqrt{s}$ change	MC template method	Symmetry method
ggF H	1.12	√	√
VBF H	1.13	√	√
VH	1.10	√	√
ttH	1.21	√	-
Z+jets	1.10	√	-
Diboson	1.10	√	-
Top-quark	1.16	√	-
W+jets	1.10	√	-
Fake bkg.	1.10	√	√
Symm bkg.	1.12	-	√

[ATL-PHYS-PUB-2022-054]

Scale Factors for Systematic Uncertainties

Uncertainties	Extrapolation SF	MC template method	Symmetry method
$\tau_{\text{had-vis}}$ ID, stat.-related	0.00	✓	-
$\tau_{\text{had-vis}}$, others	1.00	✓	-
Electron and muon	1.00	✓	✓
Flavour tagging c- and b-jets	0.50	✓	✓
Jet, others	1.00	✓	✓
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.50	✓	✓
Fake bkg., stat.-related	0.21	✓	✓
Fake bkg., others	1.00	✓	✓
Lepton eff. corr., stat.-related	0.21	-	✓
Lepton eff. corr., others	1.00	-	✓
Z bkg. modelling, PDF	0.40	✓	-
Z bkg. modelling, others	0.50	✓	-
Top-quark bkg. modelling, PDF	0.40	✓	-
Top-quark bkg. modelling, others	0.50	✓	-
Higgs modelling, PDF, ggF	0.41	✓	✓
Higgs modelling, PDF, VBF H	0.46	✓	✓
Higgs modelling, PDF, VH	0.46	✓	✓
Higgs modelling, others	0.50	✓	✓
Luminosity	0.59	✓	✓

[ATL-PHYS-PUB-2022-054]

Sensitivity Metrics

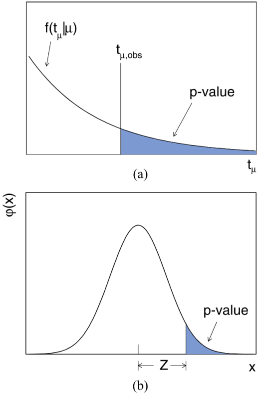
- Significance (Z) for $\mathcal{B} = 0.1\,\%$:
  - Test statistic for quantifying significance:

$$t_0 = \begin{cases} -2\ln\lambda(\mu = 0), & \hat{\mu} \geq 0 \\ 0, & \hat{\mu} < 0 \end{cases}, \quad p_0 = \int_{t_0^{\mathrm{obs}}}^{\infty} f(t_0|\mu = 0)\,\mathrm{d}t_0$$

  - Z is # of std. dev. after which one-sided gauss AUC $= p_0$
  - Claim evidence at $\geq 3\sigma$, discovery at $\geq 5\sigma$
- $95\,\%$ CL upper limits (μ_{95}) on $\mathcal{B}[\%]$:
  - Test statistic for setting upper limits:

$$t_\mu = \begin{cases} -2\ln\lambda(\mu), & \mu \geq \hat{\mu} \\ 0, & \mu < \hat{\mu} \end{cases}, \quad p_\mu = \frac{\int_{t_\mu^{\mathrm{obs}}}^{\infty} f(t_\mu|\mu)\,\mathrm{d}t_\mu}{\int_0^{t_0^{\mathrm{obs}}} f(t_0|\mu = 0)\,\mathrm{d}t_0}$$

  - μ_{95} is the smallest μ value with $p_\mu \leq 0.05$



(a)

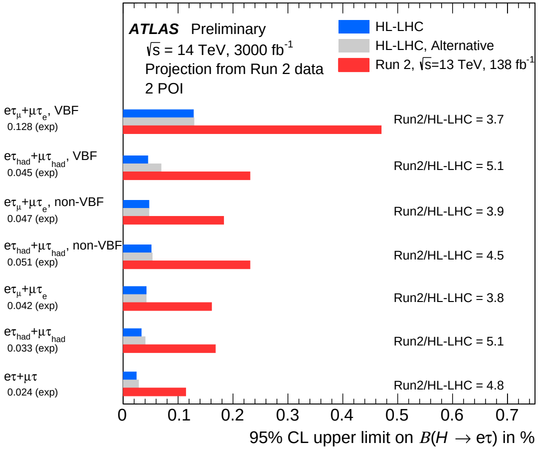
(b)

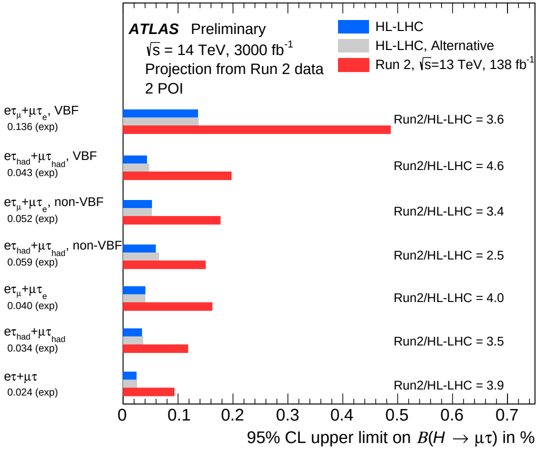
Fig. 1 (**a**) Illustration of the relation between the p-value obtained from an observed value of the test statistic t_μ. (**b**) The standard normal distribution $\varphi(x) = (1/\sqrt{2\pi})\exp(-x^2/2)$ showing the relation between the significance Z and the p-value

[Eur. Phys. J. C 71 (2011) 1554]

$\lambda(\mu)$: Profile likelihood ratio for signal strength μ

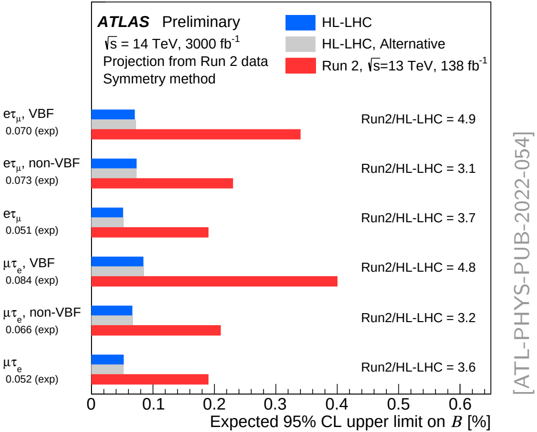
MC-Template Method Sensitivity





[ATL-PHYS-PUB-2022-054]

Symmetry Method Sensitivity

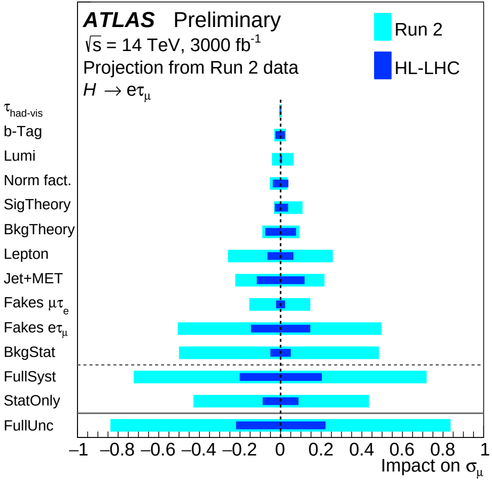


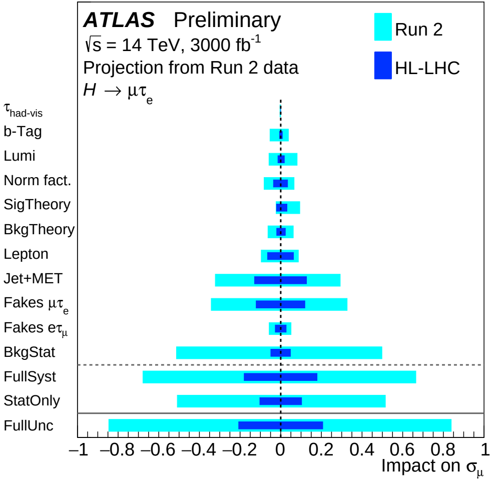
Sensitivity Comparison of Methods ($H \rightarrow \ell\tau_{\ell'}$)

Case		Symmetry method				MC-template method			
		$e\tau_\mu$		$\mu\tau_e$		$e\tau_\mu$		$\mu\tau_e$	
		Value [%]	Ratio	Value [%]	Ratio	Value [%]	Ratio	Value [%]	Ratio
Run 2	VBF	$0.34^{+0.14}_{-0.10}$		$0.40^{+0.16}_{-0.11}$		$0.47^{+0.19}_{-0.13}$		$0.49^{+0.20}_{-0.14}$	
	Non-VBF	$0.230^{+0.092}_{-0.064}$		$0.214^{+0.084}_{-0.060}$		$0.183^{+0.073}_{-0.051}$		$0.177^{+0.068}_{-0.050}$	
	Combined	$0.190^{+0.075}_{-0.053}$		$0.188^{+0.074}_{-0.053}$		$0.161^{+0.063}_{-0.045}$		$0.162^{+0.063}_{-0.045}$	
HL-LHC	VBF	$0.070^{+0.028}_{-0.020}$	4.83	$0.084^{+0.034}_{-0.024}$	4.79	$0.128^{+0.050}_{-0.036}$	3.67	$0.136^{+0.054}_{-0.038}$	3.60
	Non-VBF	$0.073^{+0.028}_{-0.020}$	3.16	$0.066^{+0.026}_{-0.019}$	3.22	$0.047^{+0.018}_{-0.013}$	3.91	$0.052^{+0.020}_{-0.014}$	3.43
	Combined	$0.051^{+0.020}_{-0.014}$	3.70	$0.052^{+0.020}_{-0.014}$	3.65	$0.042^{+0.016}_{-0.012}$	3.86	$0.040^{+0.016}_{-0.011}$	4.03

[ATL-PHYS-PUB-2022-054]

Impact of Uncertainties with MC-Template Method ($\ell\tau_{\ell'}$)





[ATL-PHYS-PUB-2022-054]