Search for lepton flavor violating decays of the Higgs boson with the ATLAS detector

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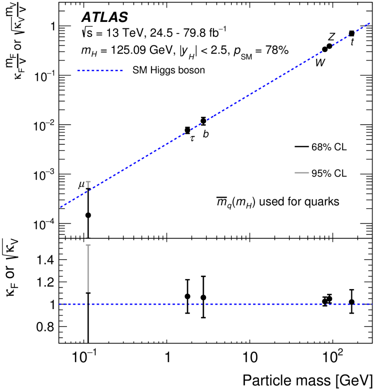
Theoretical motivation

The **discovery of the Higgs boson** has **completed the theory of the Standard Model (SM)**

- **BUT** this theory **cannot address** several **crucial issues** (e.g. dark matter, hierarchy problem, ...), thus we believe that **the SM is just the low-energy limit of a more fundamental theory**

So far, **good agreement with the SM observed** for the Higgs boson properties

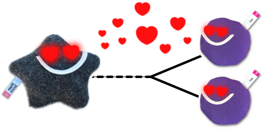
- **BUT** most of the experimental constraints apply to **couplings to** pairs of **electroweak bosons** or to **3rd generation fermions**



Search for BSM physics in Higgs boson decays to SM particles

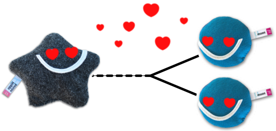
- **Lepton flavor violating (LFV) Higgs boson decays**
  - Not allowed in the SM
  - However, the observation of neutrino oscillations indicates that LFV occurs in nature

Higgs boson couplings to leptons with ATLAS



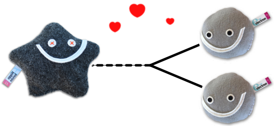
$\mathrm{BR}^{\mathrm{SM}}(H \to \tau\tau)$
$\approx 6.3 \times 10^{-2}$

- Cross-section measurements of the $H \to \tau\tau$ ($36.1\ \mathrm{fb}^{-1}$)
  Phys. Rev. D 99, 072001 (2019)



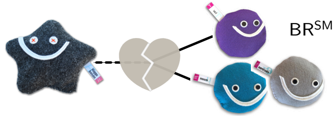
$\mathrm{BR}^{\mathrm{SM}}(H \to \mu\mu)$
$\approx 2.2 \times 10^{-4}$

- Search for $H \to \mu\mu$ ($139\ \mathrm{fb}^{-1}$)
  Phys. Lett. B 812 (2021) 135980



$\mathrm{BR}^{\mathrm{SM}}(H \to ee)$
$\approx 5.0 \times 10^{-9}$

- Search for $H \to ee$ and $H \to e\mu$ ($139\ \mathrm{fb}^{-1}$)
  Phys. Lett. B 801 (2020) 135148



$\mathrm{BR}^{\mathrm{SM}}(H \to \ell\ell') \sim 0$

- Search for $H \to \tau\ell$ ($36.1\ \mathrm{fb}^{-1}$)
  Phys. Lett. B 800 (2020) 135069

Searches for LFV $H \to \ell\tau$

- Previous ATLAS limits using 20.3 fb^{-1} of data collected at $\sqrt{s} = 8$ TeV: **BR$<$ 1.04%** for $e\tau$ and **BR$<$ 1.43%** for $\mu\tau$ with a 95% CL [EPJ C 77 (2017) 70]
- Updated using **36 fb^{-1} of 13 TeV *pp* collisions** [Phys. Lett. B 800 (2020) 135069]

Event selection:

- $\ell\tau_{\text{lep}}$: exactly 2 light-leptons of different flavor and opposite charge
- $\ell\tau_{\text{had}}$: exactly 1 τ_{had} and 1 light-lepton with opposite charge
- Veto extra leptons and *b*-jets

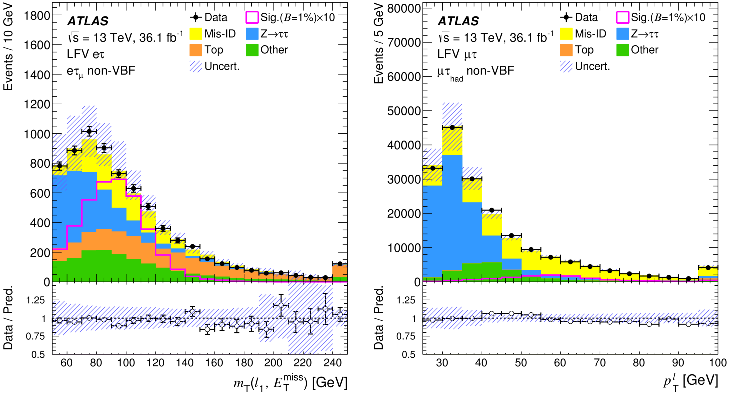
Signal regions (SRs):

- **VBF region:** $n_{\text{jets}(p_{\text{T}}>30\text{ GeV})} \geq 2$, $p_{\text{T}}^{j1} > 40$ GeV, $m_{jj} > 400$ GeV, $|\Delta\eta_{jj}| > 3$
- **nonVBF region:** fails VBF selection + additional criteria

Control regions (CRs) based on modified event selection:

- **Top CR**: at least one *b*-jet, purity 95%
- **$Z \to \tau\tau$ CR**: p_{T}(leading lepton) < 45 GeV, purity $60 - 80\%$

$H \to \ell\tau$: backgrounds



Process	Fraction in $\ell\tau_{\ell'}$	Fraction in $\ell\tau_{\text{had}}$	Modeling in final fit
$Z \to \tau\tau$	$20 - 35\%$	$45 - 55\%$	Shape from MC, norm. from CR
Top	$20 - 55\%$	$1 - 10\%$	Shape from MC, norm. from CR
Mis-ID jets or e	$5 - 25\%$	$25 - 45\%$	Fully data driven
Other backgrounds	$Z \to \mu\mu$, diboson,	$H \to \tau\tau$ and $H \to WW$	Estimated from MC

$H \to \ell\tau$: signal yield extraction

BDT algorithms used to separate signal from background $\to$ trained in each channel and SR

- Variables used in the analysis are marked with HR (indicating the five variables with the highest rank) or a bullet

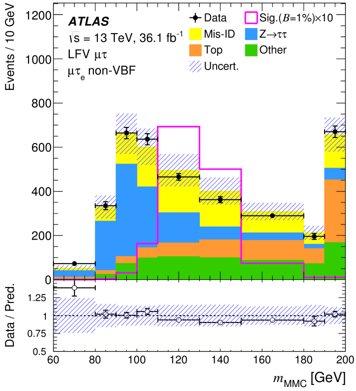
$\ell\tau_{\ell'}$ Variable	VBF	non-VBF	$\ell\tau_{\text{had}}$ Variable	VBF	non-VBF
m_{MMC}	HR	HR	m_{coll}	HR	HR
$p_{\text{T}}^{\ell_1}$	•	•	p_{T}^{ℓ}	•	HR
$p_{\text{T}}^{\ell_2}$	HR	HR	$p_{\text{T}}^{\tau_{\text{had-vis}}}$	•	HR
$\Delta R(\ell_1, \ell_2)$	HR	•	$\Delta R(\ell, \tau_{\text{had-vis}})$	•	•
$m_{\text{T}}(\ell_1, E_{\text{T}}^{\text{miss}})$	•	HR	$m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}})$	HR	•
$m_{\text{T}}(\ell_2, E_{\text{T}}^{\text{miss}})$	HR	•	$m_{\text{T}}(\tau_{\text{had-vis}}, E_{\text{T}}^{\text{miss}})$	HR	HR
$\Delta\phi(\ell_1, E_{\text{T}}^{\text{miss}})$	•	•	$\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$	HR	•
$\Delta\phi(\ell_2, E_{\text{T}}^{\text{miss}})$		HR	$\Delta\phi(\tau_{\text{had-vis}}, E_{\text{T}}^{\text{miss}})$	•	
$m(\text{j}_1, \text{j}_2)$	•		$m(\text{j}_1, \text{j}_2)$	•	
$\Delta\eta(\text{j}_1, \text{j}_2)$	HR		$\Delta\eta(\text{j}_1, \text{j}_2)$	•	
$p_{\text{T}}^{\tau}/p_{\text{T}}^{\ell_1}$		HR	$\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_{\text{T}}^{\text{miss}})$	•	•
			$E_{\text{T}}^{\text{miss}}$	HR	•
			m_{vis}		HR
			$\Delta\eta(\ell, \tau_{\text{had-vis}})$		•
			η^{ℓ}		•
			$\eta^{\tau_{\text{had-vis}}}$		•
			ϕ^{ℓ}		•
			$\phi^{\tau_{\text{had-vis}}}$		•
			$\phi(E_{\text{T}}^{\text{miss}})$		•

$H \to \ell\tau$: signal yield extraction

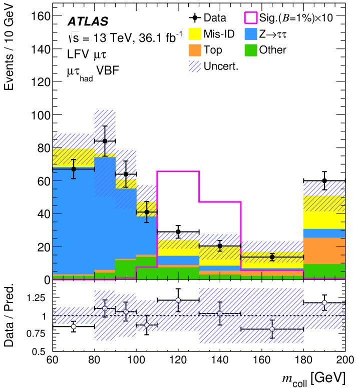
Invariant mass of the Higgs boson is one of the BDT input variables

- exhibits the highest signal-to-background separation power

$\ell\tau_\ell$: missing mass calculator $\to$ m_{MMC}



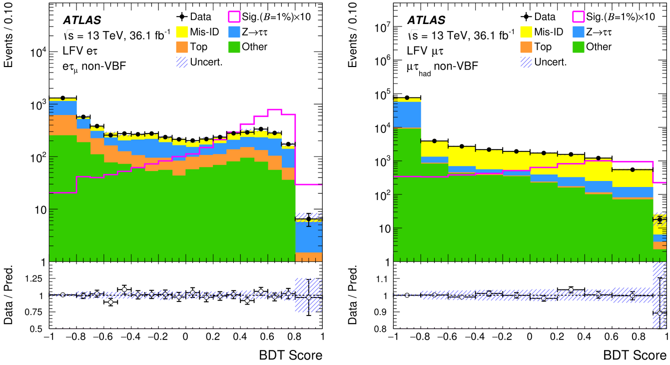
$\ell\tau_{\mathrm{had}}$: collinear approximation $\to$ m_{coll}



Pre-fit distributions of m_{MMC} and m_{coll} for $\mu\tau$ final state.

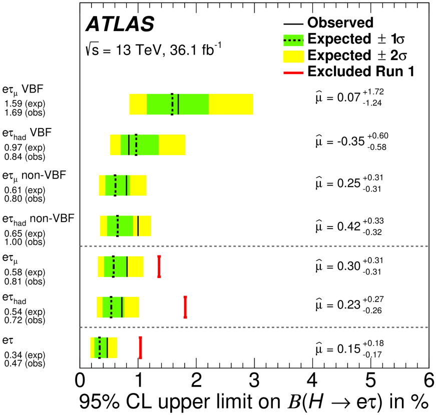
$H \to \ell\tau$: fit and systematic uncertainties

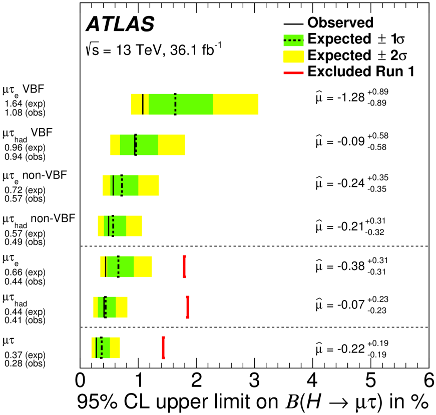
- Signal to background discrimination and extraction of yields by **simultaneous fit to SRs and CRs**
  - Fit uses **BDT score** from several kinematic variables in **SRs** and **yields in CRs**
- **Systematic uncertainties** affect the yield normalization and/or the shape of the distribution
- **Main systematic uncertainties**: from estimation of mis-identified leptons/jets and related to jet energy scale



$H \to \ell\tau$: 95% CL upper limits on the branching ratios

No significant excess is observed above the expected background from SM processes

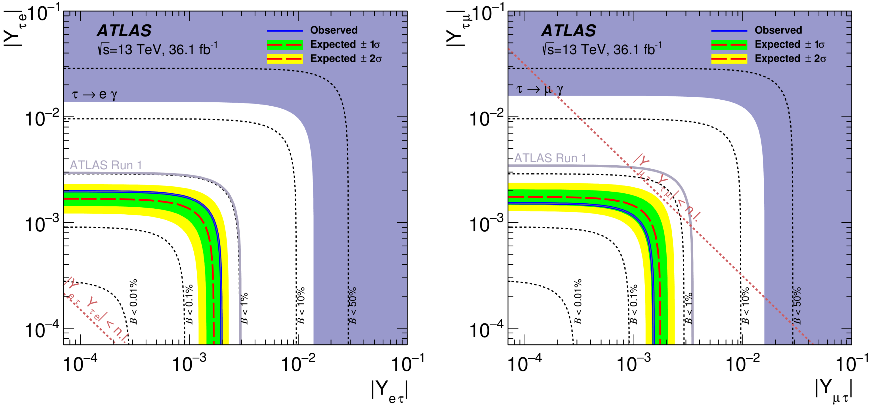




BR($H \to e\tau$) < 0.47% (0.34% exp.)

BR($H \to \mu\tau$) < 0.28% (0.37% exp.)

Constraints on the LFV Yukawa couplings $Y_{\tau\ell}$ and $Y_{\ell\tau}$



Upper limits on the absolute value of the couplings $Y_{\tau\ell}$ and $Y_{\ell\tau}$ together with the limits from the ATLAS Run-1 analysis and the most stringent indirect limits from $\tau \to \ell\gamma$ searches. Also indicated are limits corresponding to different BRs and the naturalness limit (n.l.) $Y_{\tau\ell}\, Y_{\ell\tau} \leq (m_\tau m_\ell)/v$, where v is the vacuum expectation value of the Higgs field [Phys. Rev. D, 85 (2012), Article 034011].

Summary and outlook

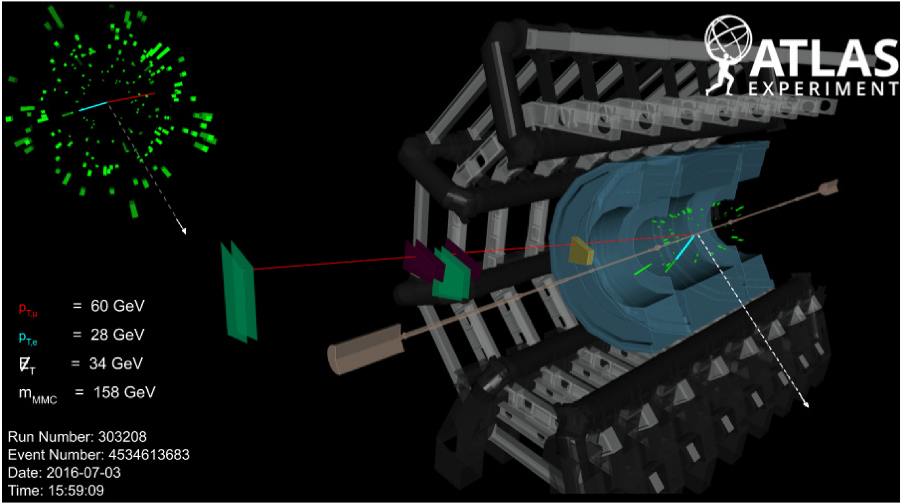
The search for LFV $H \to \ell\tau$ using 36.1 fb^{-1} of ATLAS Run-2 data-set presented

- **No** significant **deviations from the SM** predictions observed
- Observed 95% CL upper limits
  - BR($H \to e\tau$): **0.47%** $\to \sim$ 2x improvement on ATLAS Run-1 limit of 1.04 %
  - BR($H \to \mu\tau$): **0.28%** $\to \sim$ 5x improvement on ATLAS Run-1 limit of 1.43 %

We have **started** extracting physics **potential of the full Run-2 data-set**

- Analyzing 139 fb^{-1} of ATLAS Run-2 data
- Major updates to physics object reconstruction
  - τ identification done with RNN (instead of BDT)
  - Particle flow jets used
- New MVA techniques being investigated BDT $\to$ NN
- Providing simultaneous fit of $H \to e\tau$ and $H \to \mu\tau$ signal
- Results are foreseen to be published in fall 2021

BONUS SLIDES



ATLAS EXPERIMENT
$p_{T,\mu}$ = 60 GeV
$p_{T,e}$ = 28 GeV
$\not{E}_T$ = 34 GeV
m_{MMC} = 158 GeV
Run Number: 303208
Event Number: 4534613683
Date: 2016-07-03
Time: 15:59:09

LFV - event selection

Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly $1e$ and 1μ, OS	exactly 1ℓ and $1\tau_{\text{had-vis}}$, OS
	$p_T^{\ell_1} > 45$ GeV	$p_T^{\ell} > 27.3$ GeV
	$p_T^{\ell_2} > 15$ GeV	$p_T^{\tau_{\text{had-vis}}} > 25$ GeV, $\lvert\eta^{\tau_{\text{had-vis}}}\rvert < 2.4$
	$30\,\text{GeV} < m_{\text{vis}} < 150\,\text{GeV}$	$\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_T^{\text{miss}}) > -0.35$
	$p_T^e(\text{track})/p_T^e(\text{cluster}) < 1.2$ ($\mu\tau_e$ only)	$\lvert\Delta\eta(\ell, \tau_{\text{had-vis}})\rvert < 2$
	b-veto (for jets with $p_T > 25$ GeV and $\lvert\eta\rvert < 2.4$)	
VBF	Baseline	
	≥ 2 jets, $p_T^{j_1} > 40$ GeV, $p_T^{j_2} > 30$ GeV	
	$\lvert\Delta\eta(j_1, j_2)\rvert > 3$, $m(j_1, j_2) > 400$ GeV	
	–	$p_T^{\tau_{\text{had-vis}}} > 45$ GeV
Non-VBF	Baseline plus fail VBF categorization	
	$m_T(\ell_1, E_T^{\text{miss}}) > 50$ GeV	–
	$m_T(\ell_2, E_T^{\text{miss}}) < 40$ GeV	–
	$\lvert\Delta\phi(\ell_2, E_T^{\text{miss}})\rvert < 1.0$	–
	$p_T^{\tau}/p_T^{\ell_1} > 0.5$	–
Top-quark CR	inverted b-veto:	
VBF and non-VBF	≥ 1 b-tagged jet ($p_T > 25$ GeV and $\lvert\eta\rvert < 2.4$)	
$Z \to \tau\tau$ CR	inverted $p_T^{\ell_1}$ requirement:	
VBF and non-VBF	$35\,\text{GeV} < p_T^{\ell_1} < 45\,\text{GeV}$	

LFV - uncertainties

Source of uncertainty	Impact on $\mathcal{B}(H \to e\tau)$ [%] Measured	Expected	Impact on $\mathcal{B}(H \to \mu\tau)$ [%] Measured	Expected
Electron	$+0.05/-0.05$	$+0.06/-0.06$	$+0.03/-0.03$	$+0.02/-0.02$
Muon	$+0.04/-0.04$	$+0.04/-0.04$	$+0.10/-0.10$	$+0.08/-0.10$
$\tau_{\text{had-vis}}$	$+0.02/-0.02$	$+0.02/-0.02$	$+0.04/-0.04$	$+0.04/-0.05$
Jet	$+0.09/-0.08$	$+0.09/-0.09$	$+0.11/-0.12$	$+0.11/-0.12$
$E_{\text{T}}^{\text{miss}}$	$+0.02/-0.02$	$+0.02/-0.03$	$+0.05/-0.08$	$+0.03/-0.05$
b-tag	$+0.02/-0.03$	$+0.03/-0.03$	$+0.01/-0.01$	$+0.01/-0.01$
Mis-ID backg. $(\ell\tau_{\ell'})$	$+0.08/-0.07$	$+0.09/-0.08$	$+0.07/-0.07$	$+0.07/-0.07$
Mis-ID backg. $(\ell\tau_{\text{had}})$	$+0.12/-0.11$	$+0.11/-0.12$	$+0.11/-0.11$	$+0.10/-0.10$
Pile-up modelling	$+0.02/-0.01$	$+0.01/-0.01$	$+0.05/-0.03$	$+0.08/-0.06$
Luminosity	< 0.01	< 0.01	< 0.01	< 0.01
Background norm.	$+0.05/-0.04$	$+0.05/-0.03$	$+0.04/-0.02$	$+0.05/-0.03$
Theor. uncert. (backg.)	$+0.04/-0.03$	$+0.04/-0.03$	$+0.08/-0.07$	$+0.09/-0.09$
Theor. uncert. (signal)	$+0.01/-0.01$	$+0.01/-0.01$	$+0.04/-0.02$	$+0.02/-0.02$
MC statistics	$+0.04/-0.04$	$+0.03/-0.03$	$+0.04/-0.04$	$+0.05/-0.04$
Full systematic	$+0.17/-0.16$	$+0.17/-0.17$	$+0.18/-0.18$	$+0.19/-0.20$
Data statistics	$+0.07/-0.07$	$+0.07/-0.07$	$+0.07/-0.07$	$+0.08/-0.08$
Total	$+0.18/-0.17$	$+0.18/-0.18$	$+0.19/-0.19$	$+0.20/-0.21$