# Measurements of Higgs boson production in decays to two $\tau$ leptons with the ATLAS detector

### FRANK SAUERBURGER on behalf of the ATLAS Collaboration October 21, 2021

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## Motivation



[ATLAS-CONF-2020-027]

Spontaneous symmetry breaking and Yukawa interaction

$$\mathscr{L} \subset -rac{\sqrt{2}m_{ au}}{v} \left[ (ar{m{v}}_{ au}\,ar{m{\tau}})_L \phi\,m{ au}_R + ar{m{ au}}_R \phi(m{v}_{ au}\,m{ au})_L 
ight] 
ight. 
onumber \ au \lesssim -m_{ au}\,ar{m{ au}}\,m{ au} = m{ au}_L \phi\,m{ au}_R + ar{m{ au}}_R \phi(m{v}_{ au}\,m{ au})_L 
ight]$$

 $\begin{array}{c} -i\frac{m_{\tau}}{v} & \tau \\ H \\ --- & \tau \end{array}$ 

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# Production modes



#### Analysis targets four *H* production modes

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# Analysis categories



[ATLAS-CONF-2021-044]

## Analysis categories



[ATLAS-CONF-2021-044]

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# Analysis categories



[ATLAS-CONF-2021-044]

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# Background composition

#### **Dominant backgrounds**

#### Z ightarrow au au

- Monte Carlo simulation
- 70% overall, up to 90% in boosted
- Normalization from dedicated, embedded Control Regions

#### **Misidentified** $\tau$

- Data-driven estimation
- Тор
  - Monte Carlo simulation
  - Dedicated Control Regions



Signal region composition with  $100 \,\text{GeV} < m_{\tau\tau}^{\text{MMC}} < 150 \,\text{GeV}$ 

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# Simplified embedding procedure

#### Motivation

Phase space mismatch between SR ( $Z \rightarrow \tau \tau$ ) and CR ( $Z \rightarrow \ell \ell$ )



 $\rightarrow$  How to define matching CR?

#### Procedure In control region

- **Select**  $Z \rightarrow \ell \ell$  events
- Unfold l reconstruction, identification and isolation effects
- 3 Scale  $p_{\ell}$  by parametrized  $\tau$  decay effects
- 4 Reweight to account for efficiencies

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# Simplified embedding procedure



#### Procedure In control region

- **1** Select  $Z \rightarrow \ell \ell$  events
- Unfold l reconstruction, identification and isolation effects
- 3 Scale  $p_\ell$  by parametrized  $\tau$  decay effects
- Reweight to account for efficiencies

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# Simplified embedding procedure

- Kinematic distribution in embedded τ<sub>lep</sub> τ<sub>had</sub> selection
- Event selection in CR with embedded quantities
- $Z \rightarrow \ell \ell$  events assigned to exactly one channel
- Data-MC comparison in CR to normalize  $Z \rightarrow \tau \tau$  (MC) SR
- Reduced extrapolation uncertainties



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# Data-driven estimation of misidentified $\tau$

 $au_{\text{lep}} au_{\text{had}}$  and  $au_{\text{had}} au_{\text{had}}$ 

- Jets misidentified as  $\tau_{had}$
- Background estimated with fake factor method

$$N_{\mathsf{fake}}^{\mathsf{SR}} = (N_{\mathsf{Data}}^{\mathsf{anti-}\tau} - N_{\mathsf{MC}, \ \mathsf{no} \ \mathsf{jet}}^{\mathsf{anti-}\tau}) \times \mathscr{F}$$

 $au_e au_\mu$ 

- Misidentified leptons
- Data-driven matrix method

$$(N_{\text{tight/loose}}) = [\text{eff. matrix}](N_{\text{real/fake}})$$

#### For all channels Assign uncertainties O(5 - 30%)

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# Missing mass calculator

- At least two neutrinos in the final state
- Individual contributions to E<sup>miss</sup> not measured
- Perform likelihood scan using angles between measured particles and E<sup>miss</sup><sub>T</sub>
- Find most probable Higgs boson mass m<sub>MMC</sub>
- Most important discriminant



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# Machine learning

#### VBF tagger

- Targeting VBF topology (two forward jets)
- Rejecting:
   ggF and  $Z \rightarrow \tau \tau$
- Trained on jet kinematics

#### VH tagger

- Reject non-VH production modes
- Trained on jet and Higgs kinematics
- Targeted signal frac .:

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94% in VBF 1

8

Data





66% in VH 1

# 

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# Machine learning

- BDTs for *ttH* 
  - Employ two BDTs
  - Reject tt and  $Z \rightarrow \tau \tau$  background
  - Trained on jet, τ, H and E<sup>miss</sup> properties
  - Define ttH\_1 with rectangular cuts
  - ttH signal fraction in ttH\_1: 92%



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# Measured cross sections

#### Measurements for different Pols

- Total cross section
- Cross section per production mode
- 9 bins of STXS stage 1.2 3
- Results are in agreement with the SM

**Total Cross section** 

 $(\sigma \times BR)^{obs} = 2.90 \pm 0.21(\text{stat})^{+0.37}_{-0.22}(\text{syst}) \text{ pb}$ 

Total

0.5

Ω

 $\tau_e \tau_u$ 

 $\tau_{l}\tau_{had}$ 

 $\tau_{had} \tau_{had}$ 

Comb.

-Stat.

**ATLAS** Preliminary  $H \rightarrow \tau \tau$   $\sqrt{s} = 13$  TeV, 139 fb<sup>-1</sup>

Theo.

|y<sub>µ</sub>| < 2.5

(Stat., Svst.)

 $\begin{pmatrix} +0.25 & +0.32 \\ -0.24 & -0.33 \end{pmatrix}$ 

 $\begin{pmatrix} +0.10 & +0.16 \\ -0.10 & -0.13 \end{pmatrix}$ 

(+0.10 +0.15)

+0.07 +0.12

3.5

3  $(\sigma \times B)^{\text{meas}} / (\sigma \times B)^{\text{SM}}$ 

Tot.

0.42 +0.41

0.92 +0.18

0.97 +0.17

0.92 +0.13

2

2.5

1.5

# Results

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# Measured cross sections

#### Measurements for different Pols

- Total cross section
- Cross section per production mode
- 3 9 bins of STXS stage 1.2

Results are in agreement with the SM



Observation of VBF process at  $5.3\sigma$ 

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Frank Sauerburger – Measurements of  $H \rightarrow \tau \tau$  with the ATLAS detector

# Measured cross sections

STXS measurement

#### Measurement in 9 bins of STXS stage 1.2





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## Conclusion

 $\oslash$  Total measured H 
ightarrow au au cross section

 $2.90 \pm 0.21(\text{stat}) {}^{+0.37}_{-0.32}(\text{syst}) \,\text{pb}$ 

- Inclusion of four production modes
- $\oslash$  Observation of VBF H 
  ightarrow au au at 5.3  $\sigma$
- $\odot$  Improved precision<sup>†</sup> from 27% to 14%
- STXS measurements in 9 bins
- Results in agreement with SM
- More precise measurements in future with refined analysis techniques and Run 3 dataset



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#### <sup>†</sup> wrt. Phys. Rev. D **99**,072001 (2019)

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# Backup

# Signal region composition

#### Signal region composition with $100 \,\text{GeV} < m_{\tau\tau}^{\text{MMC}} < 150 \,\text{GeV}$



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# Expected signal





#### Expected signal purity

ATLAS Simulation Preliminary  $fs = 13 \text{ TeV}, 139 \text{ fb}^{-1}, H \rightarrow \tau\tau$ 



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200

180

160

140

120

100

- 80

- 60

- 40

-20

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# Systematic uncertainties

- Largest systematic uncertainties from signal theory uncertainties (8.1%)
- Largest experiemntal uncertainty (4.2%)



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## Fit structure

- Normalization of Top background from Top control regions
- Normalization of  $Z \rightarrow \tau \tau$  from kinematically embedded  $Z \rightarrow \ell \ell$



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# Signal correlation





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# Partial Run 2 dataset



[Phys. Rev. D 99,072001 (2019)]

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