Measurements of Higgs boson properties in decays to two tau leptons with the ATLAS detector

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The $H \rightarrow \tau \tau$ Decay Channel Nature 607, pages 52–59 (2022)



- $H \rightarrow \tau \tau$ BR: 6% \Rightarrow 480000 events in Run 2
- Most precisely measured Yukawa coupling
- Best channel to study lepton couplings
- This talk: Measurement of cross-sections from and test of CP violation in $\tau\tau$ decays





Production and Decay Modes JHEP 08 (2022) 175



• Split $\tau\tau$ decays into four final states

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- Not considering $\tau_e \tau_e + \tau_\mu \tau_\mu$, large and difficult to model $Z \rightarrow \ell \ell$ bkg
- Main backgrounds: $Z \rightarrow \tau \tau$, multi-jet production

- 4 Higgs boson production modes
- Target each one with dedicated event selection



ggF Categorisation JHEP 08 (2022) 175



- Focus on boosted ggF events, baseline cut $p_T(H) > 100$ GeV
- For STXS: region split in $p_T(H)$ and N_{jets} (1J, \geq 2J)

Region	boost_0	boost_1	boost_2	boost_3
$p_T(H)$ [GeV]	[100, 120]	[120, 200]	[200, 300]	> 300

Measuring 6 STXS bins total:



VBF, VH and ttH Selections JHEP 08 (2022) 175

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Main features of dedicated regions:

- VBF: $m_{jj} > 350$ GeV, $\eta(j_0) \times \eta(j_1) < 0$
- $V(\rightarrow qq)$ H: 60 GeV $< m_{jj} < 120$ GeV
- ttH (only in $\tau_{had}\tau_{had}$): Presence of additional jets, including *b*-tagged ones
- Train taggers to define signal-enriched selection
- Events passing tagger score cuts \rightarrow region "_1", rest "_0"
- In all regions, using likelihood-based mass estimate $m_{\tau\tau}^{\text{MMC}}$ in template fit





- $Z \rightarrow \ell \ell$ -enriched selections to constrain $Z \rightarrow \tau \tau$ background
- Kinematic embedding procedure to ensure compatible phase-space
- In $\tau_{\text{lep}}\tau_{\text{lep}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$, dedicated Top regions and NFs



Measured Cross-Sections JHEP 08 (2022) 175



- Cross-sections measured inclusively, per production mode and in STXS
- Inclusively, well beyond 5 σ
- Highest precision on VBF
- ggF precision better at high $p_T(H)$
- SM compatibility *p*-value: 95%



- Similar stat./syst. unc impact
- Leading syst.: Signal modelling



Strengths of the $H \rightarrow \tau \tau$ Channel



- Sensitivity to VBF among the highest
- Very sensitive to high- p_T ggF STXS bins

VBF γγ	H E H	1.36	+ 0.30 - 0.27	$\left(\begin{array}{cc} +0.21 & +0.21 \\ -0.20 & , & -0.18 \end{array} \right)$
VBF ZZ		1.33	+ 0.52 - 0.43	$\left(\begin{array}{ccc} +0.51 & +0.11 \\ -0.43 & , & -0.08 \end{array} \right)$
VBF WW		1.13	+0.19 -0.18	$\begin{pmatrix} +0.16 & +0.12 \\ -0.15 & -0.11 \end{pmatrix}$
VBF $ au au$	÷	1.00	+0.21 -0.18	$\begin{pmatrix} +0.14 & +0.15 \\ -0.13 & -0.12 \end{pmatrix}$
VBF+ggF+bbH bb	i de la companya de l	0.98	+ 0.38 - 0.36	$\left(egin{array}{ccc} +0.32 & +0.20 \\ -0.32 & , & -0.17 \end{array} ight)$
VBF+ <i>VH</i> $\mu\mu$		2.31	+ 1.33 - 1.26	$\begin{pmatrix} +1.30 & +0.27 \\ -1.24 & , & -0.22 \end{pmatrix}$

ggF STXS Bin	H ightarrow au au standalone	Combination of final states
$p_T(H)/\text{GeV} \in [200, 300]$	$1.02\substack{+0.38\\-0.36}$	$1.43^{+0.35}_{-0.33}$
$p_T(H) > 300 \text{ GeV}$ ($\in [300, 450]$ in comb.)	$1.21\substack{+0.51 \\ -0.47}$	$0.71^{+0.47}_{-0.45}$



- Origin of baryon asymmetry in the Universe still unknown
- CP-violating processes outside of the SM needed
- Higgs boson couplings could contribute, not yet experimentally excluded Effective Lagrangian:

$$\mathscr{L}_{H\tau\tau} = -\frac{m_{\tau\tau}}{v}\kappa_{\tau} \left(\underbrace{\cos(\phi_{\tau})\bar{\tau}\tau}_{\text{CP-even}} + \underbrace{\sin(\phi_{\tau})\bar{\tau}i\gamma_{5}\tau}_{\text{CP-odd}}\right)H$$

• ϕ_{τ} : CP mixing angle between even and odd components

• SM: $\phi_{\tau} = 0$, pure CP-odd: $\phi_{\tau} = 90^{\circ}$, else: CP violation

 \Rightarrow CP-odd contribution at tree-level possible!

CP-Sensitive Observable

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- Need an observable that gives insights on $\phi_{ au}$
- Acoplanarity angle $\varphi_{C\!P}^*,$ angle between tau decay planes in rest frame

$$\mathsf{d} \Gamma_{H \to \tau^+ \tau^-} \approx 1 - b(\boldsymbol{E}_+) b(\boldsymbol{E}_-) \frac{\pi^2}{16} \cos(\varphi_{CP}^* - 2\phi_\tau)$$

- b: Spectral function, quantifies spin analysing power (depends on au decay)
- E_{\pm} : Energy of charged τ decay products



Decay Mode Classification





- Definition of φ_{CP}^* depends on τ decay mode
- Considering leptonic decays and 4 τ_{had} decay modes



- Simplest case: 1p0n decay, highest ϕ_{τ} sensitivity
- Can only define φ_{CP}^* approximately in some modes, reduced ϕ_{τ} sensitivity
- Leptonic decays involve 2 neutrinos, less clear
- \Rightarrow Not considering $\tau_{lep}\tau_{lep}$ and some $\tau_{had}\tau_{had}$ decays

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m(π±,π0) [GeV]

Event Categorisation

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- "Boost" split: $p_T(H) > 140$ GeV, $\Delta R(\tau, \tau) < 1.4 \Rightarrow$ "Boost 1"
- Decay modes grouped into Loose, Medium, Tight categories based on sensitivity \Rightarrow 12 SRs
- Experimental challenge to identify and reconstruct neutral τ decay components \Rightarrow Dedicated CRs







Test of CP Violation ATLAS-CONF-2022-032

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- Change in total $H\to\tau\tau$ normalisation can come from other BSM sources than CP-odd coupling component
- But want to test only CP violation without being sensitive to this \Rightarrow Signal normalisation unconstrained in fit
- Only basing conclusion on the shape of signal, less model-dependent



- Observed ϕ_{τ} consistent with SM prediction of 0 \Rightarrow No sign of CP violation found in τ Yukawa coupling
- Pure CP-odd hypothesis excluded at 3.4σ

HL-LHC Prospects



- HL-LHC projections performed for cross-sections and $\phi_{ au}$
- Scale expected distributions to 3000 fb^{-1} and 14 TeV for each process
- Uncertainties adapted to HL-LHC environment



- Uncertainty on inclusive xsec measurement projected to be $\approx 5\%$
- Each production mode measured at least twice as precisely
- CP projection from 2019, based on 36.1 fb^{-1} study
- HL-LHC projection looks very similar to Run 2 result



- Much to learn from studying $H \rightarrow \tau \tau$ decays
- Great sensitivity to VBF and high- p_T ggF
- Basis for further interpretations of the data
- Lepton-flavour violation: See Kieran's talk tomorrow
- First ATLAS constraints on CP-odd contribution to $H\tau\tau$ coupling
- Consistent with SM prediction of no CPV, CP-odd hypothesis disfavoured

Additional Material

Correlation Between Signal Cross-Sections



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Ranking on ggF Cross-Section





Ranking on VBF Cross-Section





Ranking on VH Cross-Section





Ranking on *ttH* Cross-Section





Event Selection STXS Measurement



Criteria	$\tau_e \tau_\mu$	$\tau_{\rm lep} \tau_{\rm had}$		$\tau_{\rm had} \tau_{\rm had}$	
		$\tau_e\tau_{\rm had}$	$\tau_{\mu}\tau_{\rm had}$		
N(e)	1	1	0	0	
$N(\mu)$	1	0	1	0	
$N(\tau_{\text{had-vis}})$	0	1	1	2	
N(b-jets)	0 (85% WP)	0 (85% WP)	0 (85% WP)	0 (70% WP)	
				$(\geq 1 \text{ or } 2 \text{ in ttH categories})$	
$p_{\rm T}(e)$ [GeV]	> 15 to 27	> 27			
$p_{\rm T}(\mu) [{\rm GeV}]$	> 10 to 27.3		> 27.3		
$p_{\rm T}(\tau_{\rm had\text{-}vis})[{\rm GeV}]$		>	30	>40, 30	
Identification	$e/\mu :$ Medium	$e/\mu/\tau_{\rm had\text{-}v}$	_{is} : Medium	$\boldsymbol{\tau}_{\text{had-vis}}:$ Medium	
Isolation	$e{:}$ Loose, $\mu{:}$ Tight	e: Loose	$\mu :$ Tight		
$ \begin{array}{c} {\rm Charge} \\ E_{\rm T}^{\rm miss} ~ [{\rm GeV}] \end{array} $		Opposit >	te charge 20		
Kinematics	$\label{eq:main_states} \begin{aligned} \overline{m_{\tau\tau}^{\rm coll} > m_Z - 25{\rm GeV}} \\ 30{\rm GeV} < m_{e\mu} < 100{\rm GeV} \end{aligned}$		$70\mathrm{GeV}$		
Leading jet	$p_{\rm T} > 40 {\rm GeV}$			$p_{\rm T} > 70 \: {\rm GeV}, \eta < 3.2$	
Angular	$\begin{array}{l} \Delta R_{e\mu} < 2.0 \\ \Delta \eta_{e\mu} < 1.5 \end{array}$	$\frac{\Delta R_{\ell\tau_{\rm had}}}{ \Delta\eta_{\ell\tau_{\rm had}} }$	$ v_{vis} < 2.5$ $ v_{vis} < 1.5$	$\begin{array}{l} 0.6 < \Delta R_{\tau_{\mathrm{had}\text{-}\mathrm{vis}}\tau_{\mathrm{had}\text{-}\mathrm{vis}}} < 2.5 \\ \Delta \eta_{\tau_{\mathrm{had}\text{-}\mathrm{vis}}\tau_{\mathrm{had}\text{-}\mathrm{vis}}} < 1.5 \end{array}$	
Coll. app. x_1/x_2	$\begin{array}{l} 0.1 < x_1 < 1.0 \\ 0.1 < x_2 < 1.0 \end{array}$	0.1 < x 0.1 < x	$c_1 < 1.4$ $c_2 < 1.2$	$\begin{array}{c} 0.1 < x_1 < 1.4 \\ 0.1 < x_2 < 1.4 \end{array}$	

Combination Result - Production And Decay





Combination Result- STXS



ATLA	s	Total	Stat.
1s = 13 Te	eV, 139 fb"	Syst.	SM
m _N = 125.	09 GeV, y_j < 2.5		
P _{3M} = 94%			
			Total Stat. Syst
	0-jet, $p_{\gamma}^{\rm H}$ < 10 GeV	•	0.87 -0.19 (+0.17, -0.10
	0-jet, $10 \le p_{\gamma}^{\alpha} < 200 \text{ GeV}$		1.23 -0.13 (+0.08, -0.10
	1-jet, $p_{\gamma}^{\prime\prime} < 60 \text{ GeV}$	•	0.80 +0.37 (+0.21, +0.11
	1-jet, 60 $\leq p_{\gamma}^{\prime\prime} <$ 120 GeV	(me	1.22 -0.26 (+0.31, -0.16
	1-jet, 120 $\le p_{\gamma}^{\rm el} < 200~{\rm GeV}$	÷	0.98 +0.43 (+0.34, +0.23
pp-+H	≥ 2-jet, m _j < 350 GeV, p ^H ₇ < 120 GeV	H	0.39 -0.48 (-0.41 -0.3
	>2 -jet, $m_j < 350$ GeV, $120 \le p_j^2 < 200$ GeV	÷	0.92 +0.44 (+0.39, +0.21
	≥ 2-jet, m _j ≥ 350 GeV, p ^H ₇ < 200 GeV		1.05 +0.82 (+0.12, +0.38
	$200 \le p_{\gamma}^n < 300 \ {\rm GeV}$		1.40 +0.35 (+0.27, +0.22
	300 ≤ p ⁺ ₇ < 450 GeV	•	0.71 -0.45 (-0.42 -0.18
	$\rho_{\gamma}^{\rm V} \ge 450~{\rm GeV}$		2.00 +1.38 (+1.29 +0.6)
	s1jet	⇒	0.29 -0.83 -0.89 -0.28
	> 2-jet, mj < 350 GeV, VH topo	e	0.66 +0.50 (+0.64 +0.22
	≥ 2 -jet, $m_j < 350$ GeV, VH veto		2.46 +1.48 (+1.32 +0.64
	> 2 -jet, 350 $\times m_j < 700$ GeV, $p_j^V < 200$ GeV	•	0.92 -0.44 (-0.42 -0.2
qq-+Hqq	\geq 2-jet, 700 \leq m_{j} $<$ 1000 GeV, p_{γ}^{N} $<$ 200 GeV		1.16 -0.48 (-0.46' -0.2
	\geq 2-jet, 1000 \leq $m_{\rm g}$ $<$ 1500 GeV, $\mu_7^{\rm e}$ $<$ 200 GeV	÷•••	1.32 +0.53 (+0.44 +0.34
	\geq 2-jet, m_{j} \geq 1500 GeV, $p_{\gamma}^{\rm V}$ $<$ 200 GeV	i 🚥	1.22 +0.37 (+0.32 +0.19
	≥ 2-jet, 350 × m _j < 1000 GeV, p ^N ₇ ≥ 200 GeV		0.55 -0.51 (-0.68 -0.21
	\geq 2-jet, $m_{j} \geq$ 1000 GeV, $p_{\gamma}^{\rm V} \geq$ 200 GeV	i 🔁	1.10 +0.30 +0.14
		•••••••••••••••••	
	$p_{\gamma}^{\nu} < 75 \text{ GeV}$		3.24 +1.38 (+1.38 +0.28
	$75 \le p_{\gamma}^{\nu} \le 150 \text{ GeV}$	⇒	0.38 -0.88 (-0.81 -0.31
qq-+HV	$150 \times p_{\gamma}^{\nu} < 250 \text{ GeV}$	• ••	0.95 -0.43 (-0.32 -0.28
	$250 \times p_{\gamma}^{\nu} < 400 \text{ GeV}$	1991	1.11 -0.38 (-0.35 -0.15
	$\rho_{\gamma}^{c} \simeq 400~{\rm GeV}$	H , Maran H	1.54 -0.82 (-0.78 -0.6
		•••••••••••••••••••	
	p ² ₇ < 150 GeV	-	0.39 -0.58 (-0.42* -0.37
ogiao -+HI	$150 \times p_{\gamma}^{\nu} < 250 \text{ GeV}$	*	1.08 +0.34 (+0.27 +0.27 +0.29 +0.32 (-0.29 -0.18
	$250 \times p_{\gamma}^{\nu} < 400 \text{ GeV}$	H H	1.03 +0.43 (+0.38 +0.11
	p ² / ₇ ≥ 400 GeV	•	0.21 -0.83 (-0.77 -0.81
	•••••••••••••••••••••••••••••••••••		
	ρ ² ₇ < 60 GeV		0.77 -0.88 (-0.82 -0.2
	60 ≤ p [*] ₇ ≤ 120 GeV		0.74 -0.48 (-0.46 -0.25
đн	120 ≤ p ⁿ ₇ < 200 GeV	H	0.40 -0.44 (-0.39 -0.21
	200 x p; < 300 GeV		0.90 -0.51 (-0.45 -0.22
	300 E P; < 400 GeV	<u></u>	0.25 -0.59 (-0.50 -0.31
	ρ ⁺ / ₇ × 450 GeV	T	0.06 -1.42 (-0.99 -0.38
	-6 -4 -2 0	2 4	6
eH .			6.22 -0.18 (-0.38 -1.2



Process	Generator		PDF set		Tune	Normalisation
	ME	$_{\rm PS}$	ME	PS		
Higgs boson						
ggF	POWHEG BOX v2	Pythia 8	PDF4LHC15nnlo	CTEQ6L1	AZNLO	$N^{3}LO QCD + NLO EW$
VBF	Powheg Box v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO $QCD + NLO EW$
VH	POWHEG BOX v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO $QCD + NLO EW$
$t\bar{t}H$	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NLO QCD + NLO EW
tH	MadGraph5_ aMC@NLO	Pythia 8	CT10	NNPDF2.3L0	A14	NLO
$b \overline{b} H$	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3L0	A14	NLO
Background						
V + jets (QCD/EW)	Sherpa 2.2.1		NNPDF3.0nnlo		Sherpa	NNLO for QCD, LO for EW
tī	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
Single top	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3L0	A14	NLO
Diboson	Sherpa 2.2.1		NNPDF3.0nnlo		Sherpa	NLO