Search for the Standard Model Higgs boson in the di-tau channel with the ATLAS detector

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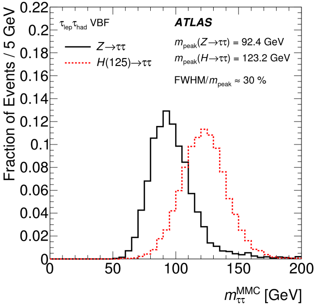
Introduction

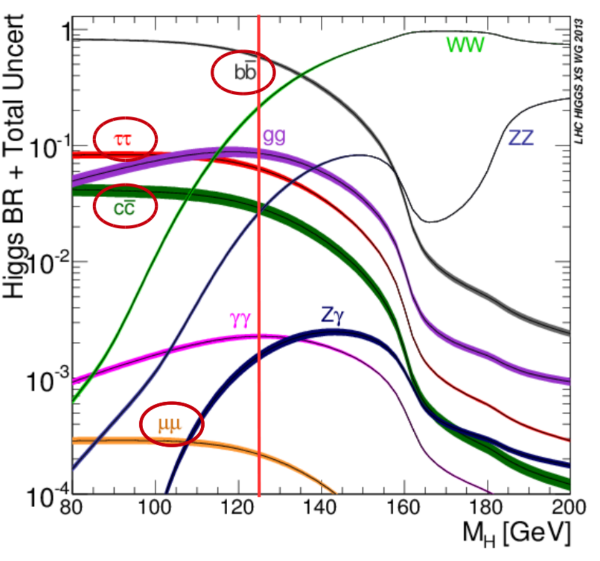
- Several reasons to study SM $H \to \tau\tau$:
  - Higgs coupling to fermions
  - Higgs CP (see talk by D. Zanzi)

- Challenging channel(s):
  - Complex final states (jets, leptons, MET, taus)
  - Numerous backgrounds (both irreducible and fake) to be understood and controlled
  - Low S/B
  - Poor M_H resolution

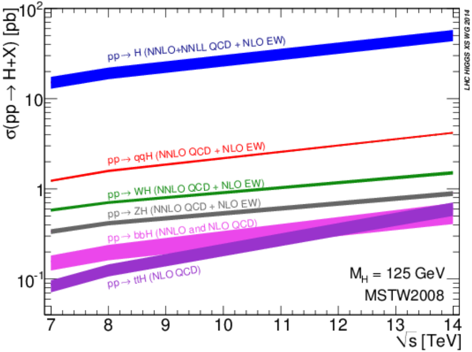


- Today: Run-1 (2011+2012) results - JHEP 04 (2015) 117
- Run-2 results (2015+2016) coming soon.

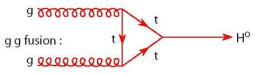
Higgs Decay to Fermions



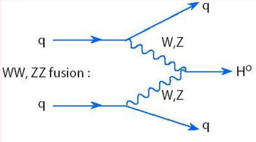
SM Higgs Production



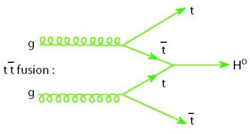
ggF



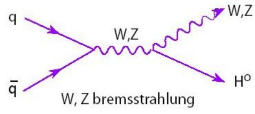
VBF



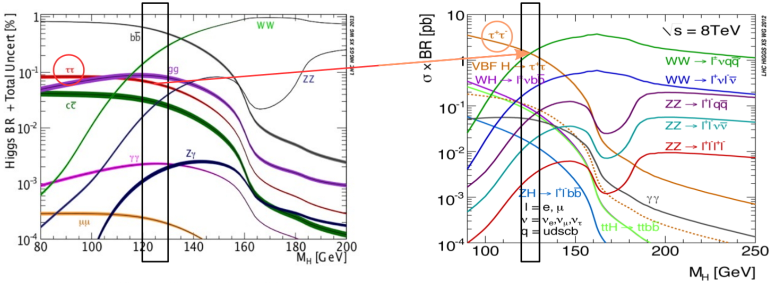
ttH

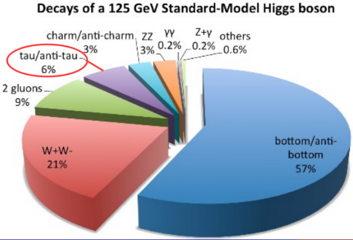


W/Z Associated Production



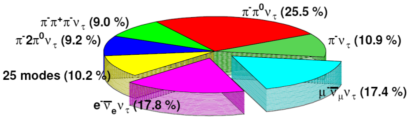
SM Higgs Decay

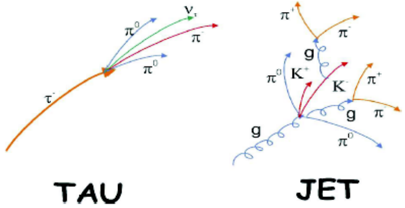




- Highest BR among the leptons.
- Low overall BR compensated using all production/decay modes.
- Presence of neutrinos in final state makes full kinematic reconstruction impossible.

ATLAS Tau Basics





Identifying hadronic τ Decays

- Hadronic decays are a well-collimated collection of charged and neutral pions.
- Large jet background at LHC.
- BDT-based τ_{had} ID:
  - 55-60%(40%) efficiency for medium (tight)
  - 1-2% (0.5%) jet acceptance.

For this reason, the tau-tau channel is actually many channels, classified by the decay of the tau: $\tau_\ell\tau_\ell$, $\tau_\ell\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$.

Analysis Strategy

- BR for each mode:
  - $H \to \tau\tau \to \tau_\ell\tau_\ell + 4\nu$ (12%)
  - $H \to \tau\tau \to \tau_\ell\tau_{\mathrm{had}} + 3\nu$ (46%)
  - $H \to \tau\tau \to \tau_{\mathrm{had}}\tau_{\mathrm{had}} + 2\nu$ (42%)
- Separate analyses **in each decay mode** allows optimization for different background compositions.
- Define analysis **categories** motivated by Higgs production modes:
  - **VBF:** target VBF topology by requiring 2 forward jets in opposite hemispheres.
  - **Boosted:** target ggF topology with Boosted Higgs to improve mass resolution.

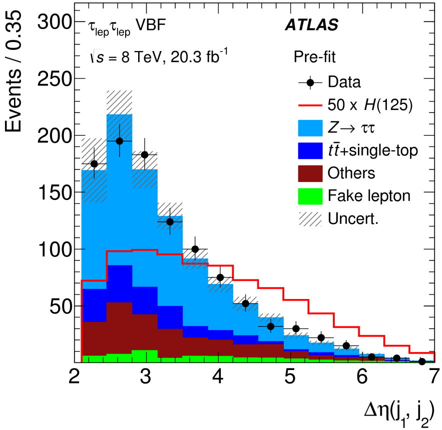
Special Considerations

- In all modes, neutrinos limit mass resolution. Use Missing Mass Calculator (MMC) to achieve 30% resolution.
- Use data-driven background models where possible.
- $Z \rightarrow \tau\tau$ is an important background to all decay modes. Use **embedding**:
  - Start with $Z \rightarrow \mu\mu$ data events, remove muons.
  - Embed MC τ in the data events.

  Improves modeling of jet/met variables, reduces systematic uncertainties, increases sample sizes!!

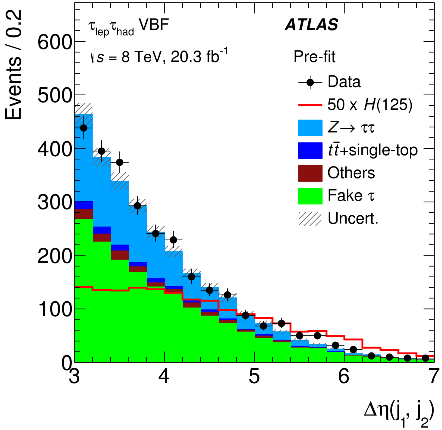
Important Backgrounds to $\tau_\ell\tau_\ell$

- $Z \to \tau\tau$ **:** embedding
- **Others:** MC normalized in data control region.
- **Top:** MC normalized in data control region.
- **Fake Leptons:** shape from data control (reverse lepton isolation), normalized to data.



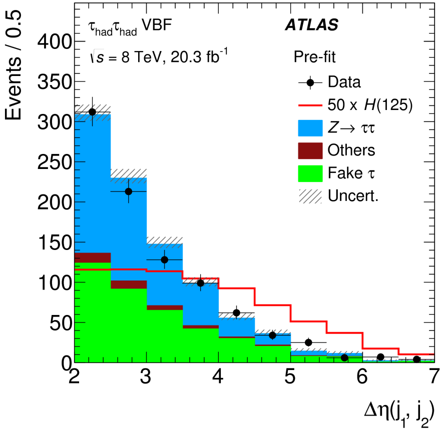
Important Backgrounds to $\tau_\ell\tau_{\rm had}$

- **$Z \to \tau\tau$:** embedding
- **Fake τ:** Includes background with jets faking taus, including W+jets and multi-jets.
- **Top:** MC normalized in data control region.
- **Others:** W+jets, $Z \to \ell\ell$, di-bosons. From MC.



Important Backgrounds to $\tau_{\rm had}\tau_{\rm had}$

- $Z \to \tau\tau$ **:** embedding
- **Fake τ:** shape from not-opposite-sign (notOS), not isolated data. Normalized by fitting $\Delta\eta(\tau\tau)$ distribution (free in final fit).
- **Others:** Shape from MC. Fake rate derived from data samples. Dominated by $W \to \tau\nu +$ jets.



(Cascading) Selection Criteria

	VBF	Boost	Rest
$\tau_\ell \tau_\ell$	$p_T(j) > 40, 25$ GeV $\Delta\eta_{jj} > 2.2$	Fail VBF $P_T^H > 100$ GeV $P_T^{j1} > 40$ GeV	-
$\tau_\ell \tau_{\rm had}$	$p_T(j) > 50, 30$ GeV $\Delta\eta_{jj} > 3.0$ $m_{\tau\tau}^{vis} > 40$GeV	Fail VBF $P_T^H > 100$ GeV	-
$\tau_{\rm had} \tau_{\rm had}$	$p_T(j) > 50, 30$ GeV $\Delta\eta_{jj} > 2.0$	Fail VBF $P_T^H > 100$ GeV	Fail VBF, Boost

- Differing background composition and sample sizes lead to different optimal settings per decay mode.
- Events which fail VBF get passed to the next category...

Poor S/B, Train 6 BDTs

	VBF	Boost
$\tau_\ell \tau_\ell$	S/B=0.02	S/B=0.01
$\tau_\ell \tau_{\text{had}}$	S/B=0.02	S/B=0.01
$\tau_{\text{had}} \tau_{\text{had}}$	S/B=0.02	S/B=0.01

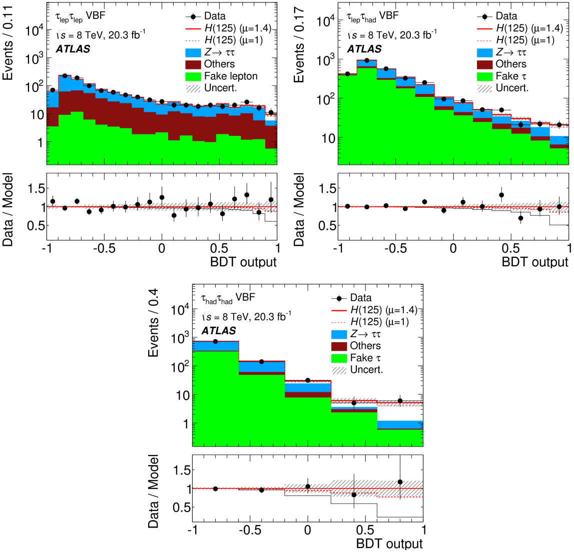
Poor S/B, Train 6 BDTs

	VBF	Boost
$\tau_\ell \tau_\ell$		
$\tau_\ell \tau_{\rm had}$		
$\tau_{\rm had} \tau_{\rm had}$		

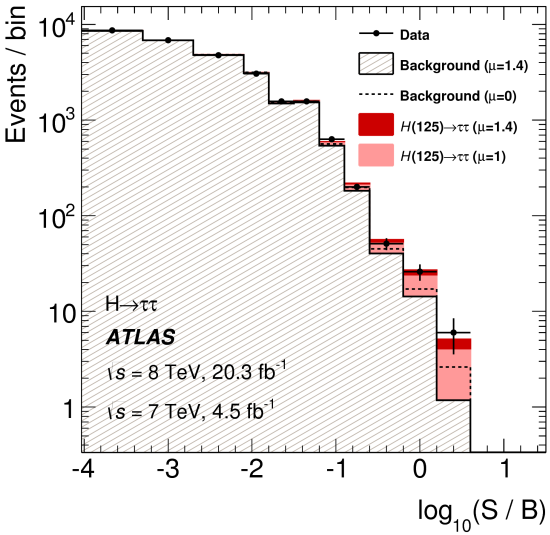
BDT Variables

Variable	VBF			Boosted		
	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
$m_{\tau\tau}^{\rm MMC}$	•	•	•	•	•	•
$\Delta R(\tau_1, \tau_2)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\rm T}^{\rm Total}$		•	•			
Sum $p_{\rm T}$					•	•
$p_{\rm T}^{\tau_1}/p_{\rm T}^{\tau_2}$					•	•
$E_{\rm T}^{\rm miss}\phi$ centrality		•	•	•	•	•
m_{ℓ,ℓ,j_1}				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi(\ell_1, \ell_2)$				•		
Sphericity				•		
$p_{\rm T}^{\ell_1}$				•		
$p_{\rm T}^{j_1}$				•		
$E_{\rm T}^{\rm miss}/p_{\rm T}^{\ell_2}$				•		
$m_{\rm T}$		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\rm jets})$	•					
$C_{\eta_1,\eta_2}(\eta_{\ell_1}) \cdot C_{\eta_1,\eta_2}(\eta_{\ell_2})$	•					
$C_{\eta_1,\eta_2}(\eta_\ell)$		•				
$C_{\eta_1,\eta_2}(\eta_{j_3})$	•					
$C_{\eta_1,\eta_2}(\eta_{\tau_1})$			•			
$C_{\eta_1,\eta_2}(\eta_{\tau_2})$			•			

Final Discriminant: BDT Score



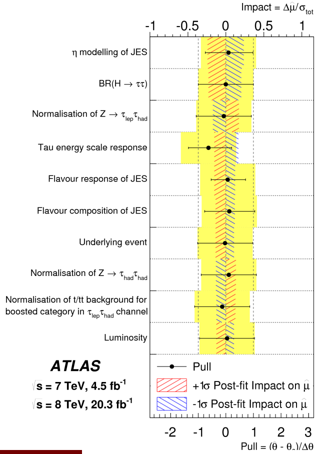
Combining Channels



Extracting Results

- Use combined, binned maximum-likelihood fit
  - Use BDT output in 6 signal categories (separate 7/8TeV)
  - Zll, top, Rest control regions to constrain backgrounds
  - Extract signal strength μ (observed/expected SM for $\sigma \times BR$)

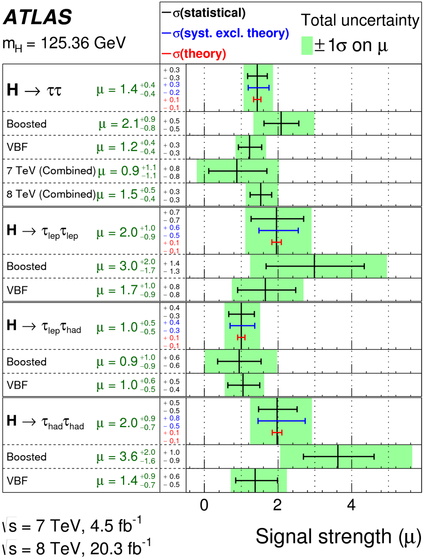
Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	$^{+0.27}_{-0.26}$
Jet energy scale	$\pm$ 0.13
Tau energy scale	$\pm$ 0.07
Tau identification	$\pm$ 0.06
Background normalisation	$\pm$ 0.12
Background estimate stat.	$\pm$ 0.10
BR $(H \to \tau\tau)$	$\pm$ 0.08
Parton shower/Underlying event	$\pm$ 0.04
PDF	$\pm$ 0.03
Total sys.	$^{+0.33}_{-0.26}$
Total	$^{+0.43}_{-0.37}$



Significances

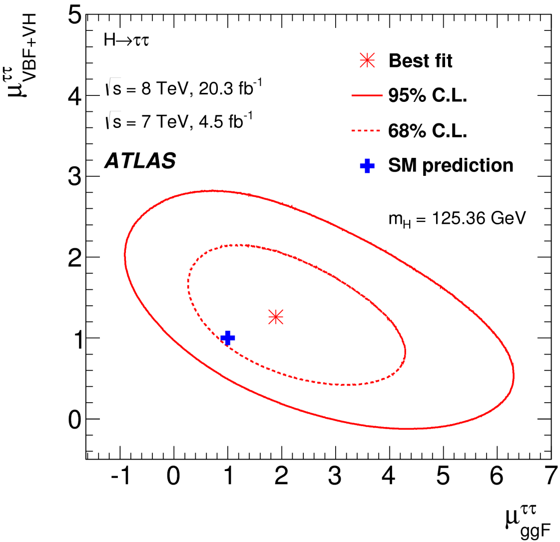
Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ VBF	1.15	1.88
$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ Boosted	0.57	1.72
$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ Total	1.25	2.40
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ VBF	2.11	2.23
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ Boosted	1.11	1.01
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ Total	2.33	2.33
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ VBF	1.70	2.23
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ Boosted	0.82	2.56
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ Total	1.99	3.25
Combined	3.43	4.54

Results



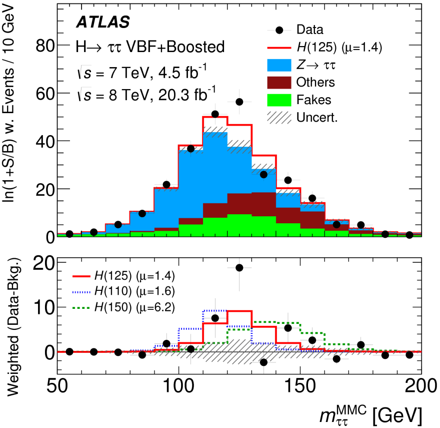
ATLAS
m_H = 125.36 GeV
σ(statistical)
σ(syst. excl. theory)
σ(theory)
Total uncertainty
±1σ on μ
H → ττ μ = 1.4 +0.4 −0.4
Boosted μ = 2.1 +0.9 −0.8
VBF μ = 1.2 +0.4 −0.4
7 TeV (Combined) μ = 0.9 +1.1 −1.1
8 TeV (Combined) μ = 1.5 +0.5 −0.4
H → τlepτlep μ = 2.0 +1.0 −0.9
Boosted μ = 3.0 +2.0 −1.7
VBF μ = 1.7 +1.0 −0.9
H → τlepτhad μ = 1.0 +0.5 −0.5
Boosted μ = 0.9 +1.0 −0.9
VBF μ = 1.0 +0.6 −0.5
H → τhadτhad μ = 2.0 +0.9 −0.7
Boosted μ = 3.6 +2.0 −1.6
VBF μ = 1.4 +0.9 −0.7
0
2
4
√s = 7 TeV, 4.5 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
Signal strength (μ)

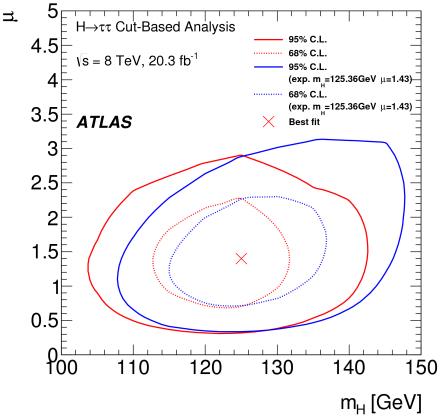
Results



H→ττ
√s = 8 TeV, 20.3 fb-1
√s = 7 TeV, 4.5 fb-1
ATLAS
Best fit
95% C.L.
68% C.L.
SM prediction
mH = 125.36 GeV
μ^ττ_VBF+VH
μ^ττ_ggF
-1 0 1 2 3 4 5 6 7
0 1 2 3 4 5

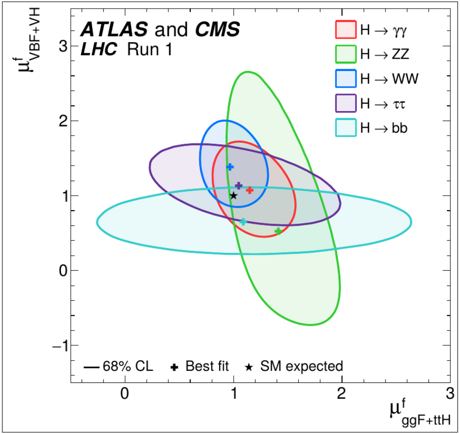
Is it at 125 GeV?





Summary and Conclusions

- Results from di-tau channels with full 2011+2012 datasets presented
- Combination with CMS yields a 5.5σ observation with $\mu = 1.12^{+0.25}_{-0.23}$
- 2016 dataset (13 TeV) now exceeds $25 fb^{-1}$. New results coming soon!



EXTRA SLIDES

MC Generators

Signal ($m_H = 125$ GeV)	MC generator	$\sigma\times$BR [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	POWHEG [36–39] + PYTHIA8 [40]	1.22	NNLO+NNLL	[42–47, 78]
VBF, $H \to \tau\tau$	POWHEG + PYTHIA8	0.100	(N)NLO	[51–53, 78]
WH, $H \to \tau\tau$	PYTHIA8	0.0445	NNLO	[56, 78]
ZH, $H \to \tau\tau$	PYTHIA8	0.0262	NNLO	[56, 78]
Background	**MC generator**	**$\sigma\times$BR [pb] $\sqrt{s} = 8$ TeV**		
$W(\to \ell\nu)$, ($\ell = e, \mu, \tau$)	ALPGEN [71]+PYTHIA8	36800	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV$< m_{\ell\ell} <$ 2 TeV	ALPGEN+PYTHIA8	3910	NNLO	[79, 80]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV$< m_{\ell\ell} <$ 60 GeV	ALPGEN+HERWIG [81]	13000	NNLO	[79, 80]
VBF $Z/\gamma^*(\to \ell\ell)$	SHERPA [82]	1.1	LO	[82]
$t\bar{t}$	POWHEG + PYTHIA8	253†	NNLO+NNLL	[83–88]
Single top : Wt	POWHEG + PYTHIA8	22†	NNLO	[89]
Single top : s-channel	POWHEG + PYTHIA8	5.6†	NNLO	[90]
Single top : t-channel	AcerMC [74]+PYTHIA6 [67]	87.8†	NNLO	[91]
$q\bar{q} \to WW$	ALPGEN+HERWIG	54†	NLO	[92]
$gg \to WW$	GG2WW [73]+HERWIG	1.4†	NLO	[73]
WZ, ZZ	HERWIG	30†	NLO	[92]
$H \to WW$	same as for $H \to \tau\tau$ signal	4.7†		

Trigger Thresholds

$\sqrt{s} = 7$ TeV

Trigger	Trigger level thresholds, p_T [GeV]	Analysis level thresholds [GeV] $\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Single electron	20–22	$e\mu$: $p_T^e > 22-24$, $p_T^\mu > 10$	$e\tau$: $p_T^e > 25$, $p_T^\tau > 20$	–
Single muon	18	$\mu\mu$: $p_T^{\mu 1} > 20$, $p_T^{\mu 2} > 10$; $e\mu$: $p_T^\mu > 20$, $p_T^e > 15$	$\mu\tau$: $p_T^\mu > 22$, $p_T^\tau > 20$	–
Di-electron	12/12	ee: $p_T^{e1} > 15$, $p_T^{e2} > 15$	–	–
Di-τ_{had}	29/20	–	–	$\tau\tau$: $p_T^{\tau 1} > 35$, $p_T^{\tau 2} > 25$

$\sqrt{s} = 8$ TeV

Trigger	Trigger level thresholds, p_T [GeV]	Analysis level thresholds [GeV] $\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Single electron	24	$e\mu$: $p_T^e > 26$, $p_T^\mu > 10$; ee: $p_T^{e1} > 26$, $p_T^{e2} > 15$	$e\tau$: $p_T^e > 26$, $p_T^\tau > 20$	–
Single muon	24	–	$\mu\tau$: $p_T^\mu > 26$, $p_T^\tau > 20$	–
Di-electron	12/12	ee: $p_T^{e1} > 15$, $p_T^{e2} > 15$	–	–
Di-muon	18/8	$\mu\mu$: $p_T^{\mu 1} > 20$, $p_T^{\mu 2} > 10$	–	–
Electron+muon	12/8	$e\mu$: $p_T^e > 15$, $p_T^\mu > 10$	–	–
Di-τ_{had}	29/20	–	–	$\tau\tau$: $p_T^{\tau 1} > 35$, $p_T^{\tau 2} > 25$

Preselection

Channel	Preselection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	Exactly two isolated opposite-sign leptons Events with $\tau_{\rm had}$ candidates are rejected 30 GeV$< m_{\tau\tau}^{\rm vis} <$ 100 (75) GeV for DF (SF) events $\Delta\phi_{\ell\ell} < 2.5$ $E_{\rm T}^{\rm miss} >$ 20 (40) GeV for DF (SF) events $E_{\rm T}^{\rm miss,HPTO} >$ 40 GeV for SF events $p_{\rm T}^{\ell_1} + p_{\rm T}^{\ell_2} >$ 35 GeV Events with a b-tagged jet with $p_{\rm T} >$ 25 GeV are rejected $0.1 < x_{\tau_1}, x_{\tau_2} < 1$ $m_{\tau\tau}^{\rm coll} > m_Z - 25$ GeV
$\tau_{\rm lep}\tau_{\rm had}$	Exactly one isolated lepton and one medium $\tau_{\rm had}$ candidate with opposite charges $m_{\rm T} <$ 70 GeV Events with a b-tagged jet with $p_{\rm T} >$ 30 GeV are rejected
$\tau_{\rm had}\tau_{\rm had}$	One isolated medium and one isolated tight opposite-sign $\tau_{\rm had}$-candidate Events with leptons are vetoed $E_{\rm T}^{\rm miss} >$ 20 GeV $E_{\rm T}^{\rm miss}$ points between the two visible taus in ϕ, or $\min[\Delta\phi(\tau, E_{\rm T}^{\rm miss})] < \pi/4$ $0.8 < \Delta R(\tau_{\rm had_1}, \tau_{\rm had_2}) < 2.4$ $\Delta\eta(\tau_{\rm had_1}, \tau_{\rm had_2}) < 1.5$
Channel	VBF category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least two jets with $p_{\rm T}^{j_1} >$ 40 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 2.2$
$\tau_{\rm lep}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} >$ 50 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $\Delta\eta(j_1, j_2) > 3.0$ $m_{\tau\tau}^{\rm vis} >$ 40 GeV
$\tau_{\rm had}\tau_{\rm had}$	At least two jets with $p_{\rm T}^{j_1} >$ 50 GeV and $p_{\rm T}^{j_2} >$ 30 GeV $p_{\rm T}^{j_2} >$ 35 GeV for jets with $\|\eta\| > 2.4$ $\Delta\eta(j_1, j_2) > 2.0$
Channel	Boosted category selection cuts
$\tau_{\rm lep}\tau_{\rm lep}$	At least one jet with $p_{\rm T} >$ 40 GeV
All	Failing the VBF selection $p_{\rm T}^{H} >$ 100 GeV

Control Regions

Process	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
$Z \to \ell\ell$-enriched	$80 < m_{\tau\tau}^{\mathrm{vis}} < 100$ GeV (same-flavour)		
Top control region	Invert b-jet veto	Invert b-jet veto and $m_{\mathrm{T}} > 40$ GeV	
Rest category			Pass preselection, Fail VBF and Boosted selections
$Z \to \tau\tau$-enriched	$m_{\tau\tau}^{\mathrm{HPTO}} < 100$ GeV	$m_{\mathrm{T}} < 40$ GeV and $m_{\tau\tau}^{\mathrm{MMC}} < 110$ GeV	
Fake-enriched	Same sign τ decay products	Same sign τ decay products	
W-enriched		$m_{\mathrm{T}} > 70$ GeV	
Mass sideband			$m_{\tau\tau}^{\mathrm{MMC}} < 110$ GeV or $m_{\tau\tau}^{\mathrm{MMC}} > 150$ GeV

Scale Factors

Channel	Background	Scale factors (CR) VBF	Boosted
$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	Top	0.99 ± 0.07	1.01 ± 0.05
	$Z \to ee$	0.91 ± 0.16	0.98 ± 0.10
	$Z \to \mu\mu$	0.97 ± 0.13	0.96 ± 0.08
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	Top	0.84 ± 0.08	0.96 ± 0.04

Systematic Variations

Source	Relative signal and background variations [%]											
	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ VBF		$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ Boosted		$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ VBF		$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ Boosted		$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ VBF		$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ Boosted	
	S	B	S	B	S	B	S	B	S	B	S	B
Experimental												
Luminosity	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1	±2.8	±0.1
Tau trigger*	–	–	–	–	–	–	–	–	$^{+7.7}_{-8.8}$	< 0.1	$^{+7.8}_{-8.9}$	< 0.1
Tau identification	–	–	–	–	±3.3	±1.2	±3.3	±1.8	±6.6	±3.8	±6.6	±5.1
Lepton ident. and trigger*	$^{+1.4}_{-2.1}$	$^{+1.3}_{-1.7}$	$^{+1.4}_{-2.1}$	$^{+1.1}_{-1.5}$	±1.8	±0.5	±1.8	± 0.8	–	–	–	–
b-tagging	±1.3	±1.6	±1.6	±1.6	< 0.1	±0.2	±0.4	±0.2	–	–	–	–
τ energy scale†	–	–	–	–	±2.4	±1.3	±2.4	±0.9	±2.9	±2.5	±2.9	±2.5
Jet energy scale and resolution†	$^{+8.5}_{-9.1}$	±9.2	$^{+4.7}_{-4.9}$	$^{+3.7}_{-3.0}$	$^{+9.5}_{-8.7}$	±1.0	±3.9	±0.4	$^{+10.1}_{-8.0}$	±0.3	$^{+5.1}_{-6.2}$	±0.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft scale & resolution	$^{+0.0}_{-0.2}$	$^{+0.0}_{-1.2}$	$^{+0.0}_{-0.1}$	$^{+0.0}_{-1.2}$	$^{+0.8}_{-0.3}$	±0.2	±0.4	< 0.1	±0.5	±0.2	±0.1	< 0.1
Background Model												
Modelling of fake backgrounds*†	–	± 1.2	–	±1.2	–	±2.6	–	±2.6	–	±5.2	–	±0.6
Embedding†	–	$^{+3.8}_{-4.3}$	–	$^{+6.0}_{-6.5}$	–	±1.5	–	±1.2	–	±2.2	–	±3.3
$Z \to \ell\ell$ normalisation*	–	± 2.1	–	±0.7	–	–	–	–	–	–	–	–
Theoretical												
Higher-order QCD corrections †	$^{+11.3}_{-9.1}$	±0.2	$^{+19.8}_{-15.3}$	±0.2	$^{+9.7}_{-7.6}$	±0.2	$^{+19.3}_{-14.7}$	±0.2	$^{+10.7}_{-8.2}$	< 0.1	$^{+20.3}_{-15.4}$	< 0.1
UE/PS	± 1.8	< 0.1	± 5.9	< 0.1	±3.8	< 0.1	±2.9	< 0.1	±4.6	< 0.1	±3.8	< 0.1
Generator modelling	±2.3	< 0.1	±1.2	< 0.1	±2.7	< 0.1	±1.3	< 0.1	±2.4	< 0.1	±1.2	< 0.1
EW corrections	±1.1	< 0.1	±0.4	< 0.1	±1.3	< 0.1	±0.4	< 0.1	±1.1	< 0.1	±0.4	< 0.1
PDF †	$^{+4.5}_{-5.8}$	± 0.3	$^{+6.2}_{-8.0}$	± 0.2	$^{+3.9}_{-3.6}$	± 0.2	$^{+6.6}_{-6.1}$	± 0.2	$^{+4.3}_{-4.0}$	± 0.2	$^{+6.3}_{-5.8}$	± 0.1
BR ($H \to \tau\tau$)	± 5.7	–	±5.7	–	±5.7	–	±5.7	–	± 5.7	–	±5.7	–

$\tau_\ell \tau_\ell$ Yields

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
$Z \to \tau\tau$	589 ± 24	9.7 ± 1.0	1.99 ± 0.34	2190 ± 80	33.7 ± 2.3	11.3 ± 1.3
Fake background	57 ± 12	1.2 ± 0.6	0.55 ± 0.35	100 ± 40	2.9 ± 1.3	0.6 ± 0.4
Top	131 ± 19	0.9 ± 0.4	0.89 ± 0.33	380 ± 50	9.8 ± 2.1	4.3 ± 1.0
Others	196 ± 17	3.0 ± 0.4	1.7 ± 0.6	400 ± 40	8.3 ± 1.6	2.6 ± 0.7
ggF: $H \to WW$ $(m_H = 125\ GeV)$	2.9 ± 0.8	0.12 ± 0.04	0.11 ± 0.04	7.7 ± 2.3	0.43 ± 0.13	0.24 ± 0.08
VBF: $H \to WW$	3.4 ± 0.4	0.40 ± 0.06	0.38 ± 0.08	1.65 ± 0.18	0.102 ± 0.017	< 0.1
$WH:\ H \to WW$	< 0.1	< 0.1	< 0.1	0.90 ± 0.10	< 0.1	< 0.1
$ZH:\ H \to WW$	< 0.1	< 0.1	< 0.1	0.59 ± 0.07	< 0.1	< 0.1
ggF: $H \to \tau\tau$ $(m_H = 125GeV)$	9.8 ± 3.4	0.73 ± 0.26	0.35 ± 0.14	21 ± 8	2.4 ± 0.9	1.3 ± 0.5
VBF: $H \to \tau\tau$	13.3 ± 4.0	2.7 ± 0.7	3.3 ± 0.9	5.5 ± 1.5	0.95 ± 0.26	0.49 ± 0.13
$WH:\ H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	3.8 ± 1.0	0.44 ± 0.12	0.22 ± 0.06
$ZH:\ H \to \tau\tau$	0.14 ± 0.04	< 0.1	< 0.1	2.0 ± 0.5	0.21 ± 0.06	0.113 ± 0.031
Total background	980 ± 22	15.4 ± 1.8	5.6 ± 1.4	3080 ± 50	55 ± 4	19.2 ± 2.1
Total signal	24 ± 6	3.5 ± 0.9	3.6 ± 1.0	33 ± 10	4.0 ± 1.2	2.1 ± 0.6
Data	1014	16	11	3095	61	20

$\tau_\ell \tau_{\text{had}}$ Yields

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	1680 ± 50	8.2 ± 0.9	5.2 ± 0.7	5640 ± 160	51.0 ± 2.5	22.3 ± 1.8
$Z \to \tau\tau$	877 ± 29	7.6 ± 0.9	4.2 ± 0.7	6210 ± 170	57.5 ± 2.8	41.1 ± 3.2
Top	82 ± 15	0.3 ± 0.4	0.5 ± 0.4	380 ± 50	12 ± 4	4.8 ± 1.5
$Z \to \ell\ell(\ell \to \tau_{\text{had}})$	54 ± 26	1.0 ± 0.7	0.30 ± 0.28	200 ± 50	13 ± 4	8.6 ± 3.5
Diboson	63 ± 11	1.0 ± 0.4	0.48 ± 0.20	430 ± 40	9.7 ± 2.2	4.7 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125 GeV$)	16 ± 6	1.0 ± 0.4	1.2 ± 0.6	60 ± 20	9.2 ± 3.2	10.1 ± 3.4
VBF: $H \to \tau\tau$	31 ± 8	4.5 ± 1.1	9.1 ± 2.2	16 ± 4	2.5 ± 0.6	2.9 ± 0.7
WH : $H \to \tau\tau$	0.6 ± 0.4	< 0.1	< 0.1	9.1 ± 2.3	1.3 ± 0.4	1.9 ± 0.5
ZH : $H \to \tau\tau$	0.16 ± 0.07	< 0.1	< 0.1	4.6 ± 1.2	0.77 ± 0.20	0.93 ± 0.24
Total background	2760 ± 40	18.1 ± 2.3	10.7 ± 2.7	12860 ± 110	143 ± 6	82 ± 6
Total signal	48 ± 12	5.5 ± 1.3	10.3 ± 2.5	89 ± 26	14 ± 4	16 ± 4
Data	2830	22	21	12952	170	92

$\tau_{\text{had}}\tau_{\text{had}}$ Yields

Process/Category	VBF			Boosted		
BDT output bin	All bins	Second to last bin	Last bin	All bins	Second to last bin	Last bin
Fake background	370 ± 18	2.3 ± 0.9	0.57 ± 0.29	645 ± 26	35 ± 4	0.65 ± 0.33
Others	37 ± 5	0.67 ± 0.22	< 0.1	89 ± 11	15.9 ± 2.0	0.92 ± 0.22
$Z \to \tau\tau$	475 ± 16	0.6 ± 0.7	0.6 ± 0.4	2230 ± 70	93 ± 4	5.4 ± 1.6
ggF: $H \to \tau\tau$ ($m_H = 125GeV$)	8.0 ± 2.7	0.67 ± 0.23	0.53 ± 0.20	21 ± 8	9.1 ± 3.3	1.6 ± 0.6
VBF: $H \to \tau\tau$	12.0 ± 3.1	1.8 ± 0.5	3.4 ± 0.9	6.3 ± 1.6	2.8 ± 0.7	0.52 ± 0.13
$WH: H \to \tau\tau$	0.25 ± 0.07	< 0.1	< 0.1	4.0 ± 1.1	1.9 ± 0.5	0.41 ± 0.11
$ZH: H \to \tau\tau$	0.16 ± 0.04	< 0.1	< 0.1	2.4 ± 0.6	1.13 ± 0.30	0.23 ± 0.06
Total background	883 ± 18	3.6 ± 1.3	1.2 ± 1.0	2960 ± 50	143 ± 6	7.0 ± 1.8
Total signal	20 ± 5	2.5 ± 0.6	3.9 ± 1.0	34 ± 10	15 ± 4	2.7 ± 0.8
Data	892	5	6	3020	161	10