



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

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on behalf of the ATLAS Collaboration
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Content

Cross-section measurements of the Higgs boson decaying into a pair of τ -leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

[PRD 99 \(2019\) 072001](#), [arXiv:1811.08856](#) and [HEPData](#)

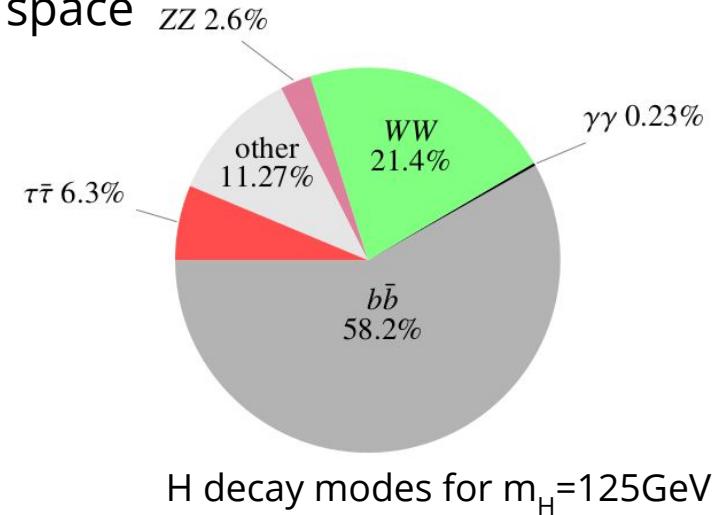
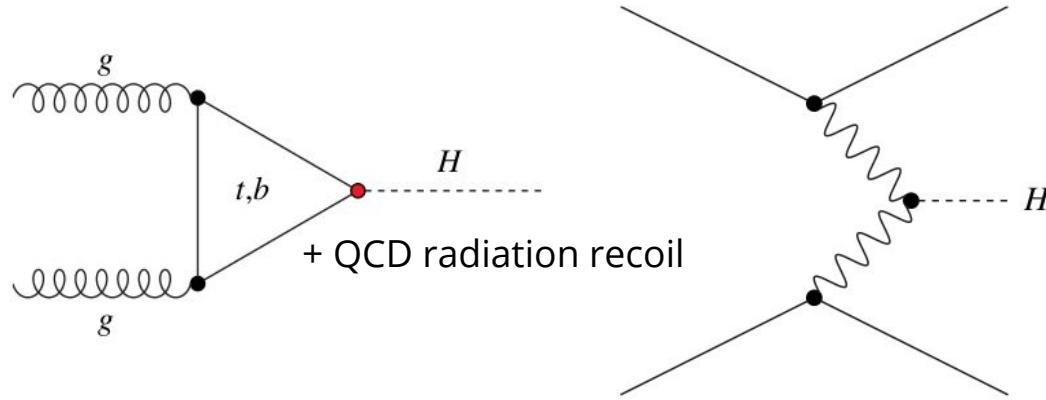
CP properties

Run 1 VBF CP with Optimal Observable [EPJC 76 \(2016\) 658](#)

HL-LHC Prospects with acoplanarity angle φ_{CP}^* [ATL-PHYS-PUB-2019-008](#)

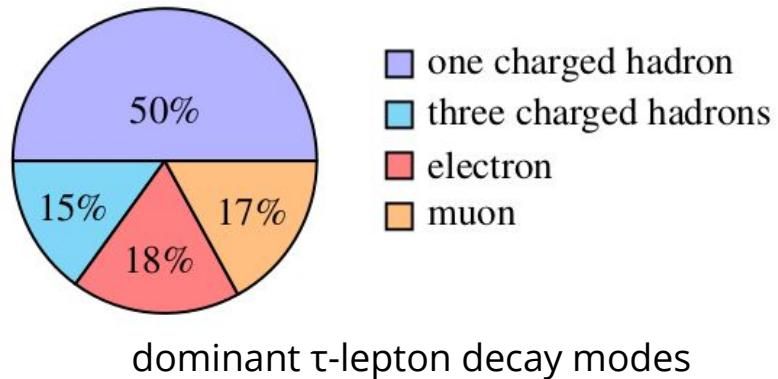
Motivation for $H \rightarrow \tau\tau$

- observation of new type of fundamental interaction: fermion-scalar aka Yukawa
- heaviest lepton means large $H \rightarrow \tau\tau$ branching fraction
- unique decays with characteristic detector signatures
- access to ggF with large boost and VBF phase space



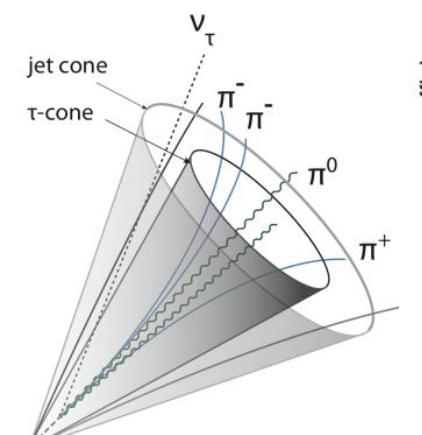
ATLAS $H \rightarrow \tau\tau$ analysis in Run 2

- LHC pp collision data recorded in 2015-2016 corresponding to 36.1 fb^{-1}
- general purpose detector ATLAS
- split into 3 general categories according to combinations of characteristic τ -lepton decays: $\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$

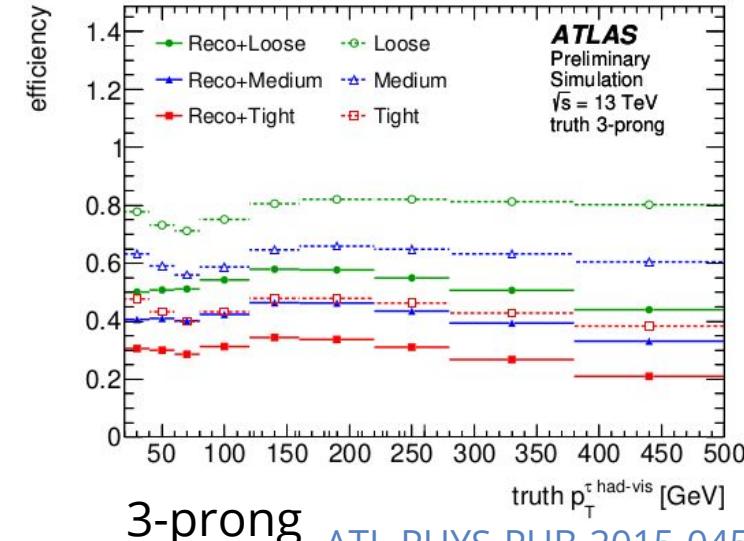
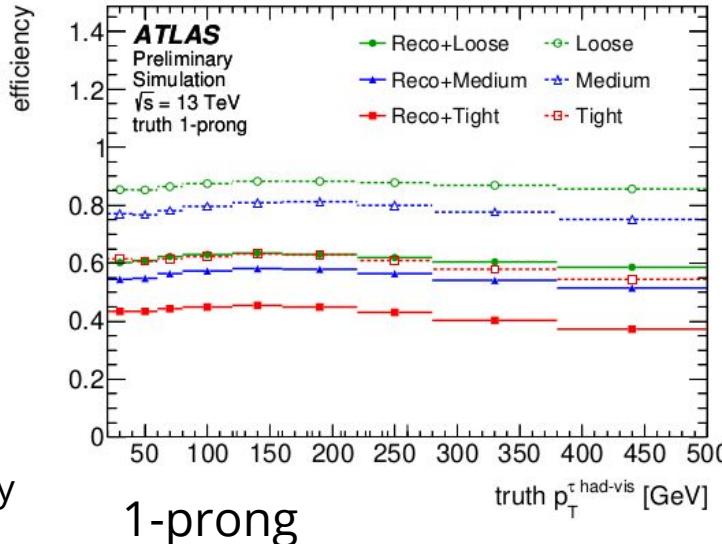


Tau lepton reconstruction

- leptonic decays are reconstructed as electron/muon + missing energy
- hadronic decays are reconstructed as jets and identified with MVA tagger
 - momentum from calo and track information with MVA regressor
 - typical efficiencies 40-60% (1-prong) and 30-50% (3-prong)



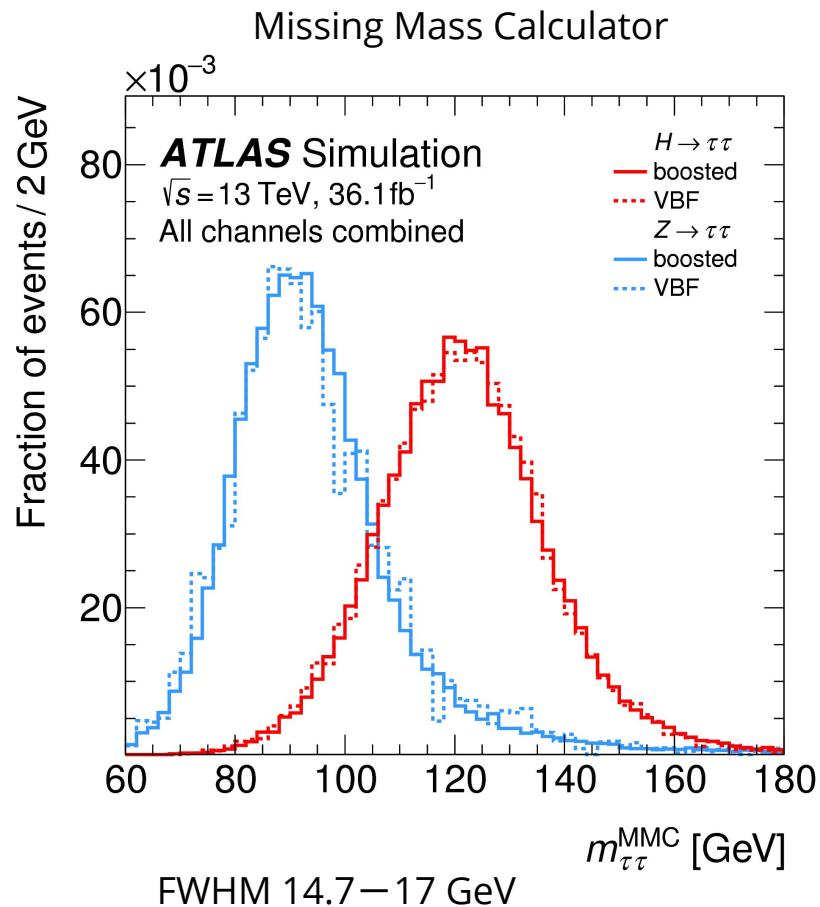
example 3-prong decay



[ATL-PHYS-PUB-2015-045](#)

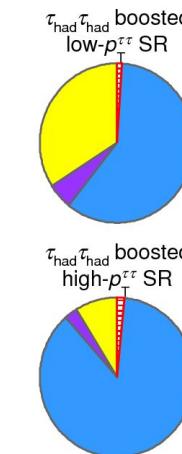
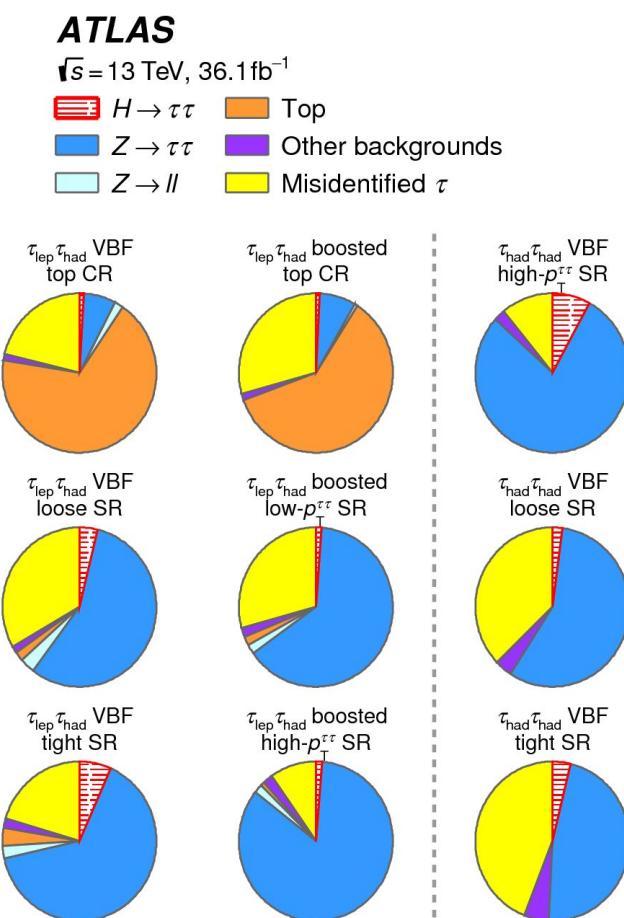
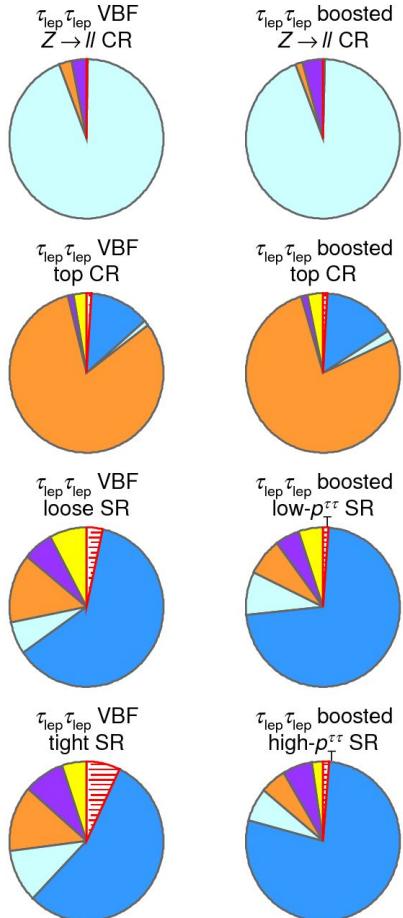
Backgrounds

- $Z \rightarrow \tau\tau$ is dominant.
broad mass peak can still discriminate against $H \rightarrow \tau\tau$
- $Z \rightarrow ee/\mu\mu$ is relevant for $\tau_{\text{lep}}\tau_{\text{lep}}$ categories
- misidentified τ (mostly τ_{had}) from multijets and W+jets
- top quark pair with leptonic decay and missed b-tag
- other: VV, single top



Event categories

- cut-based selection
define 19 categories
- 6 enriched in $Z \rightarrow \ell\ell$ and
Top quark pair background
- 13 enriched in **signal**



Background estimation

source of background	template	normalisation
Z $\rightarrow\tau\tau$	MC*	Data fit
Z $\rightarrow ee/\mu\mu$	MC*	Data fit
misidentified τ	$\tau_{\text{lep}}\tau_{\text{lep}}$: Data (invert ID/Iso) $\tau_{\text{lep}}\tau_{\text{had}}$: Data (invert ID) $\tau_{\text{had}}\tau_{\text{had}}$: Data (invert charge cut)	Data (CR extrapolation) Data (CR extrapolation) Data fit
top quark pair	MC	Data fit
other	MC	theory XS

*extensively validated in dedicated Z $\rightarrow ee/\mu\mu$ event categories

Statistical model

- profile likelihood fit to binned MMC observable
- free parameters for background (9) and signal (1-3) normalisation
- ~200 parameters for systematic uncertainties constrained by auxiliary measurements

$\tau_{\text{lep}} \tau_{\text{lep}}$	$\tau_{\text{lep}} \tau_{\text{had}}$	$\tau_{\text{had}} \tau_{\text{had}}$	CRs	Total
VBF 7+5 Boosted 8+7	VBF 6+6 Boosted 6+6	VBF 6+6+6 Boosted 10+10	6 (1 per region)	95

Number of bins in fit

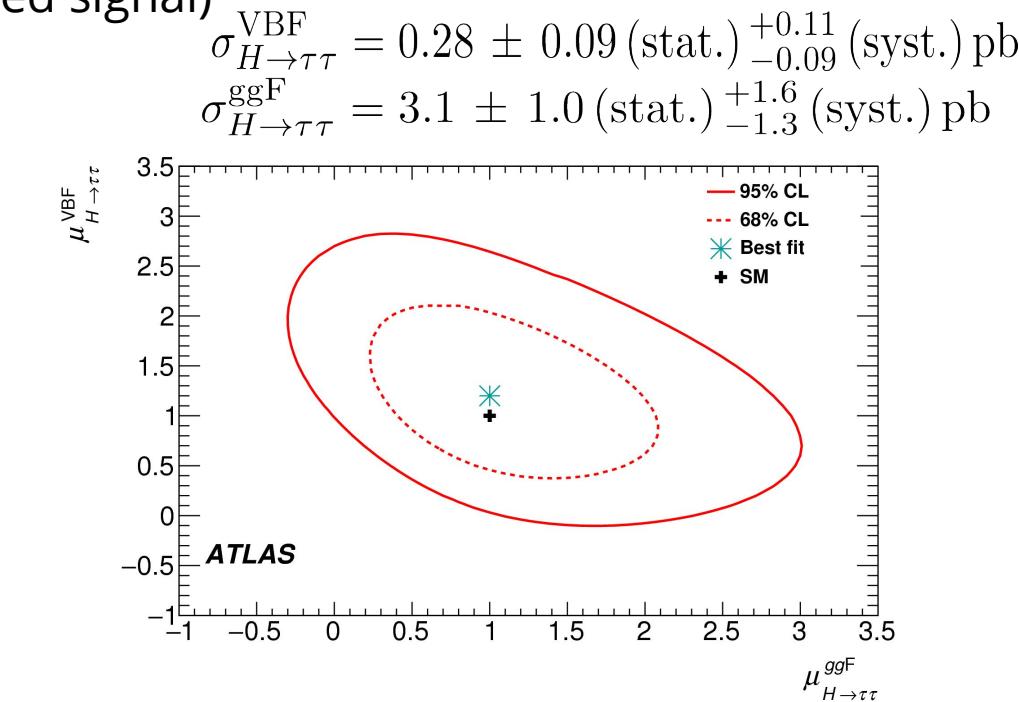
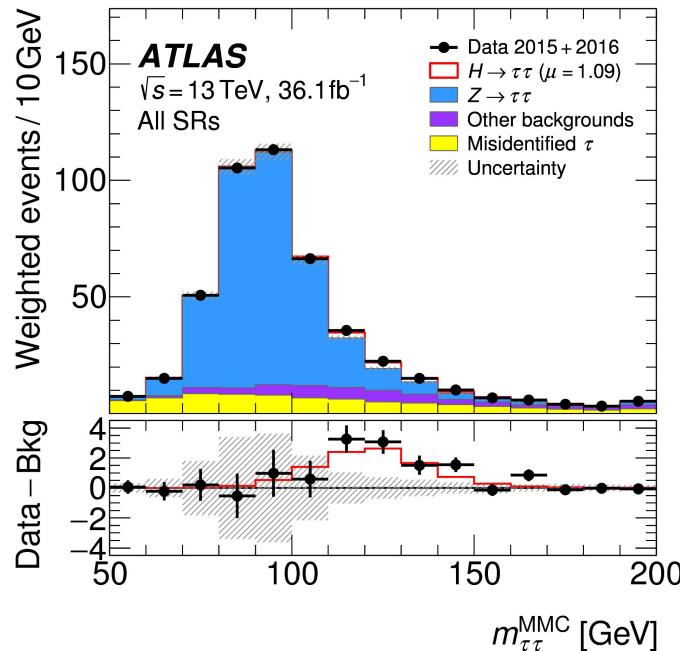
Impact of uncertainties

- systematic uncertainties dominate
- ggF prediction in exclusive NJet selections
- MC sample size
- Jet calibration via MET and MMC

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H \rightarrow \tau\tau}$ [%]	
	Observed	Expected
Theoretical uncert. in signal	+13.4 / -8.7	+12.0 / -7.8
Background statistics	+10.8 / -9.9	+10.1 / -9.7
Jets and E_T^{miss}	+11.2 / -9.1	+10.4 / -8.4
Background normalization	+6.3 / -4.4	+6.3 / -4.4
Misidentified τ	+4.5 / -4.2	+3.4 / -3.2
Theoretical uncert. in background	+4.6 / -3.6	+5.0 / -4.0
Hadronic τ decays	+4.4 / -2.9	+5.5 / -4.0
Flavor tagging	+3.4 / -3.4	+3.0 / -2.3
Luminosity	+3.3 / -2.4	+3.1 / -2.2
Electrons and muons	+1.2 / -0.9	+1.1 / -0.8
Total systematic uncert.	+23 / -20	+22 / -19
Data statistics	± 16	± 15
Total	+28 / -25	+27 / -24

Results

- clear Higgs signal observed in ditau decay
- sizable correlation between ggF and VBF measurement due to mix of signal in categories (10-30% misassigned signal)



Results cont.

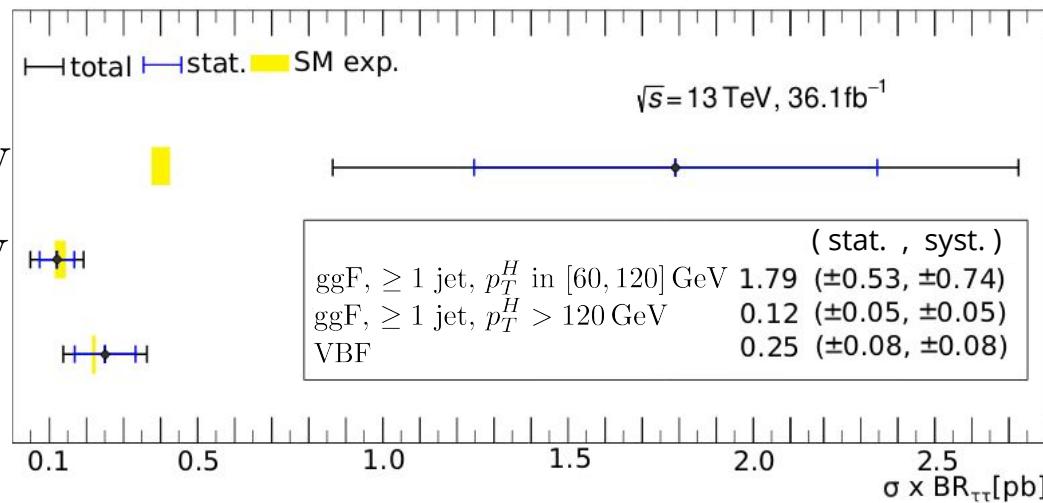
- Significance wrt background-only hypothesis 4.4σ (expected 4.1σ)
- in combination with Run 1 results: 6.4σ (expected 5.4σ)
→ standalone observation by ATLAS!
- measured cross sections times branching ratios match theoretical prediction
- $|y_H| < 2.5$

ggF, ≥ 1 jet, p_T^H in $[60, 120]$ GeV

ggF, ≥ 1 jet, $p_T^H > 120$ GeV

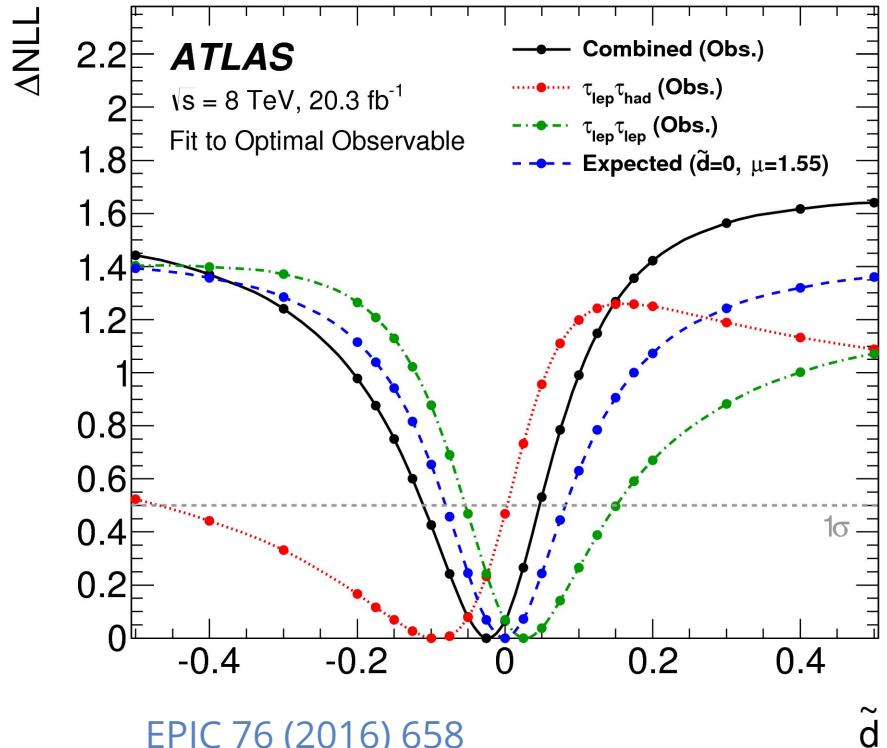
VBF

from Tab. 11 in
[arXiv:1811.08856](https://arxiv.org/abs/1811.08856)

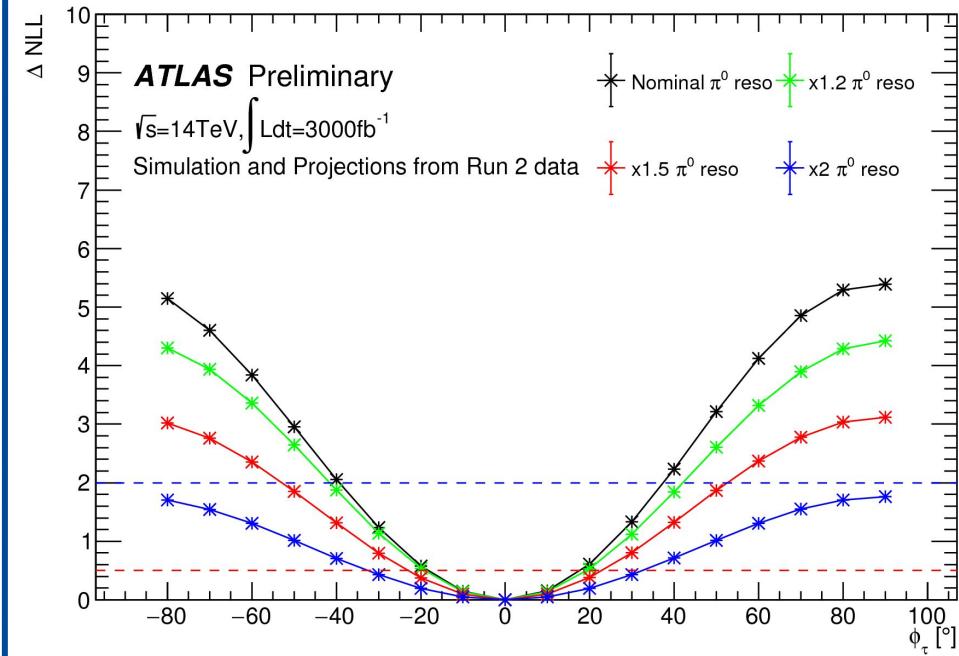


CP properties: EFT for CP even/odd mixing

Run 1 analysis of VBF $H \rightarrow \tau\tau$ events targeting HVV vertex (production)



HL-LHC prospects for $H \rightarrow \tau\tau$ events targeting Hff vertex (decay)



[ATL-PHYS-PUB-2019-008](#)

Conclusion

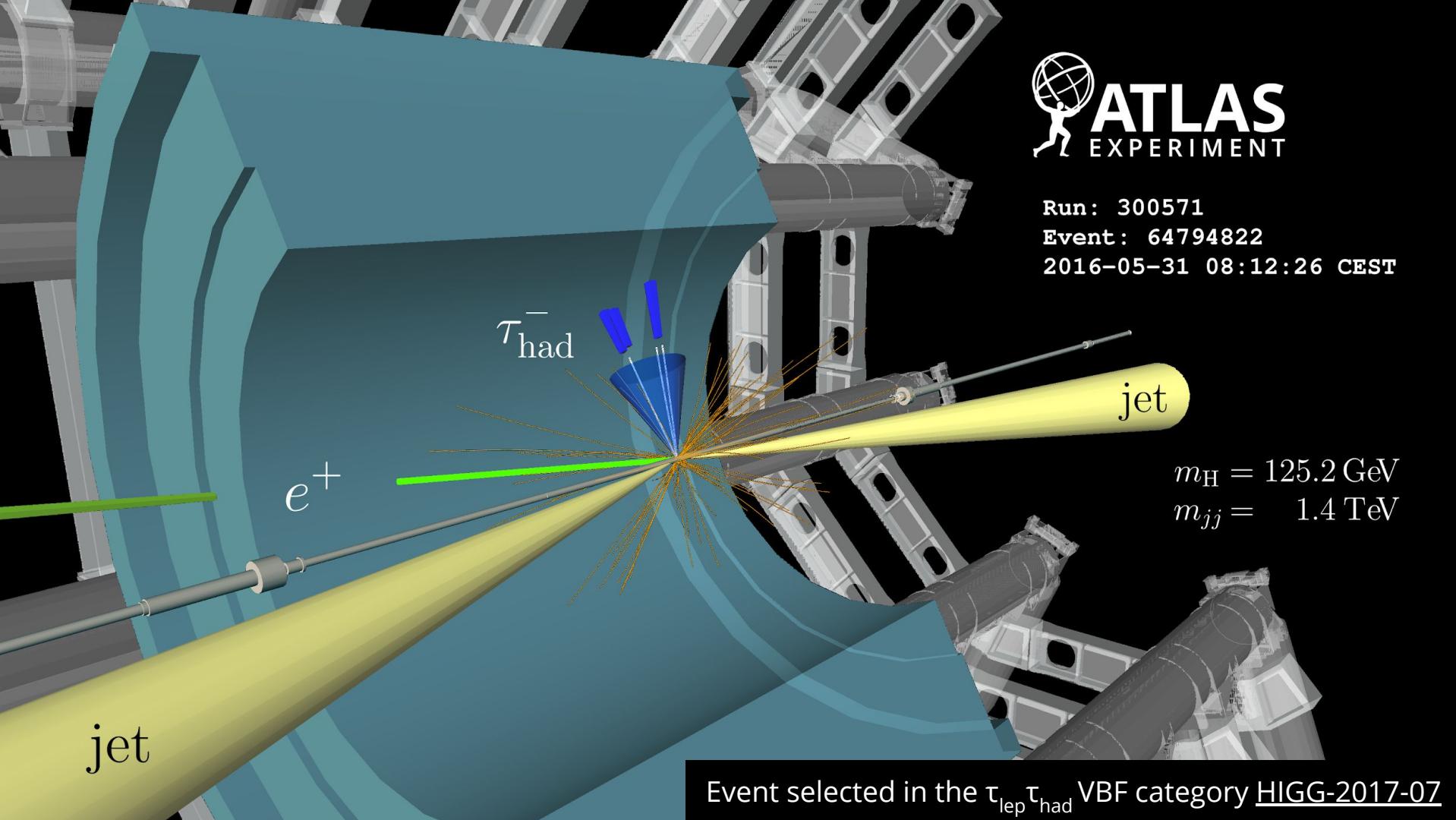
- observation of $H \rightarrow \tau\tau$ decays by ATLAS
- cross section measurements agree with predictions
- important contribution to observation and determination of Yukawa couplings
- CP properties of HVV and Hff vertices accessible as well with possibility of 95% CL exclusion limits



Run: 300571

Event: 64794822

2016-05-31 08:12:26 CEST



jet

τ^-_{had}

e^+

jet

$m_H = 125.2 \text{ GeV}$
 $m_{jj} = 1.4 \text{ TeV}$

Event selected in the $\tau_{\text{lep}}\tau_{\text{had}}$ VBF category [HIGG-2017-07](#)

Supporting material

MC processes

Table 1: Monte Carlo generators used to describe all signal and background processes together with the corresponding PDF set and the model of parton showering, hadronization and underlying event (UEPS). In addition, the order of the total cross-section calculation is given. The total cross section for VBF production is calculated at approximate-NNLO QCD. More details are given in the text.

Process	Monte Carlo generator	PDF	UEPS	Cross-section order
ggF	POWHEG-Box v2	PDF4LHC15 NNLO	PYTHIA 8.212	$N^3\text{LO}$ QCD + NLO EW
VBF	POWHEG-Box v2	PDF4LHC15 NLO	PYTHIA 8.212	$\sim\text{NNLO}$ QCD + NLO EW
VH	POWHEG-Box v2	PDF4LHC15 NLO	PYTHIA 8.212	NNLO QCD + NLO EW
$t\bar{t}H$	MG5_aMC@NLO v2.2.2	NNPDF30LO	PYTHIA 8.212	NLO QCD + NLO EW
$W/Z + \text{jets}$	SHERPA 2.2.1	NNPDF30NNLO	SHERPA 2.2.1	NNLO
$VV/V\gamma^*$	SHERPA 2.2.1	NNPDF30NNLO	SHERPA 2.2.1	NLO
$t\bar{t}$	POWHEG-Box v2	CT10	PYTHIA 6.428	NNLO+NNLL
Wt	POWHEG-Box v1	CT10F4	PYTHIA 6.428	NLO

[arXiv:1811.08856](https://arxiv.org/abs/1811.08856)

Event preselection

Table 3: Summary of the event selection requirements for the three analysis channels that are applied in addition to the respective lepton p_T requirements listed in Table 2. $E_T^{\text{miss, hard}}$ is an alternative E_T^{miss} calculated only from the physics objects without the soft-track term. The transverse mass (m_T) is calculated from E_T^{miss} and the momentum of the selected light lepton. The visible momentum fractions x_1 and x_2 of the respective τ -lepton and the collinear di- τ mass ($m_{\tau\tau}^{\text{coll}}$) are calculated in the collinear approximation [98].

$e\ell/\mu\mu$	$\tau_{\text{lep}} \tau_{\text{lep}}$	$e\mu$	$\tau_{\text{lep}} \tau_{\text{had}}$	$\tau_{\text{had}} \tau_{\text{had}}$
	$N_{e/\mu}^{\text{loose}} = 2, N_{\tau_{\text{had-vis}}}^{\text{loose}} = 0$		$N_{e/\mu}^{\text{loose}} = 1, N_{\tau_{\text{had-vis}}}^{\text{loose}} = 1$	$N_{e/\mu}^{\text{loose}} = 0, N_{\tau_{\text{had-vis}}}^{\text{loose}} = 2$
	e/μ : Medium, gradient iso.		e/μ : Medium, gradient iso.	
			$\tau_{\text{had-vis}}$: Medium	$\tau_{\text{had-vis}}$: Tight
		Opposite charge	Opposite charge	Opposite charge
		$m_{\tau\tau}^{\text{coll}} > m_Z - 25 \text{ GeV}$		
		$30 < m_{\ell\ell} < 75 \text{ GeV}$	$30 < m_{\ell\ell} < 100 \text{ GeV}$	
		$E_T^{\text{miss}} > 55 \text{ GeV}$	$E_T^{\text{miss}} > 20 \text{ GeV}$	$E_T^{\text{miss}} > 20 \text{ GeV}$
		$E_T^{\text{miss, hard}} > 55 \text{ GeV}$	$E_T^{\text{miss}} > 20 \text{ GeV}$	$E_T^{\text{miss}} > 20 \text{ GeV}$
		$\Delta R_{\tau\tau} < 2.0$	$\Delta R_{\tau\tau} < 2.5$	$0.8 < \Delta R_{\tau\tau} < 2.5$
		$ \Delta\eta_{\tau\tau} < 1.5$	$ \Delta\eta_{\tau\tau} < 1.5$	$ \Delta\eta_{\tau\tau} < 1.5$
		$0.1 < x_1 < 1.0$	$0.1 < x_1 < 1.4$	$0.1 < x_1 < 1.4$
		$0.1 < x_2 < 1.0$	$0.1 < x_2 < 1.2$	$0.1 < x_2 < 1.4$
		$p_T^{j_1} > 40 \text{ GeV}$	$p_T^{j_1} > 40 \text{ GeV}$	$p_T^{j_1} > 70 \text{ GeV}, \eta_{j_1} < 3.2$
		$N_{b\text{-jets}} = 0$	$N_{b\text{-jets}} = 0$	

arXiv:1811.08856

Event categorisation

Table 4: Definition of the VBF and boosted analysis categories and of their respective signal regions (SRs). The selection criteria, which are applied in addition to those described in Table 3, are listed for each channel. The VBF high- $p_T^{\tau\tau}$ SR is only defined for the $\tau_{\text{had}}\tau_{\text{had}}$ channel, resulting in a total of seven VBF SRs and six boosted SRs. All SRs are exclusive and their yields add up to those of the corresponding VBF and boosted inclusive regions.

Signal Region	Inclusive	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
VBF	High- $p_T^{\tau\tau}$	$p_T^{j_2} > 30 \text{ GeV}$ $ \Delta\eta_{jj} > 3$ $m_{jj} > 400 \text{ GeV}$ $\eta_{j_1} \cdot \eta_{j_2} < 0$	—	$p_T^{\tau\tau} > 140 \text{ GeV}$ $\Delta R_{\tau\tau} < 1.5$
	Tight	$m_{jj} > 800 \text{ GeV}$	$m_{jj} > 500 \text{ GeV}$ $p_T^{\tau\tau} > 100 \text{ GeV}$	Not VBF high- $p_T^{\tau\tau}$ $m_{jj} > (1550 - 250 \cdot \Delta\eta_{jj}) \text{ GeV}$
	Loose	Central leptons	Not VBF tight	Not VBF high- $p_T^{\tau\tau}$ and not VBF tight
Boosted	High- $p_T^{\tau\tau}$	Not VBF	$p_T^{\tau\tau} > 140 \text{ GeV}$ $\Delta R_{\tau\tau} < 1.5$	
	Low- $p_T^{\tau\tau}$	$p_T^{\tau\tau} > 100 \text{ GeV}$	Not boosted high- $p_T^{\tau\tau}$	

arXiv:1811.08856

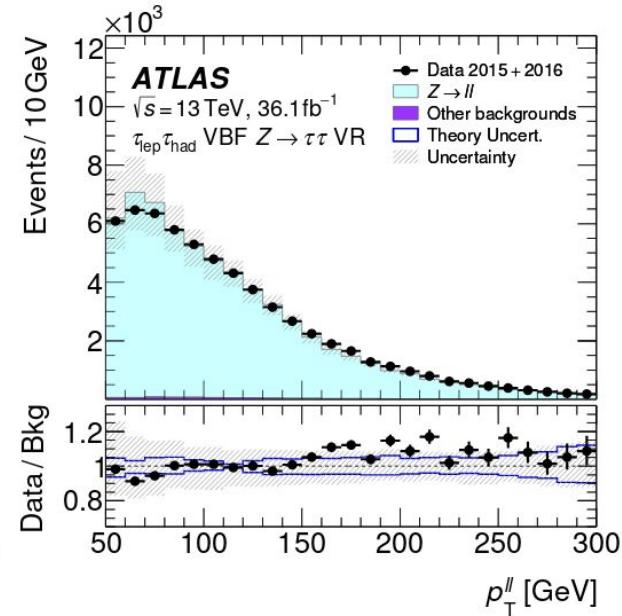
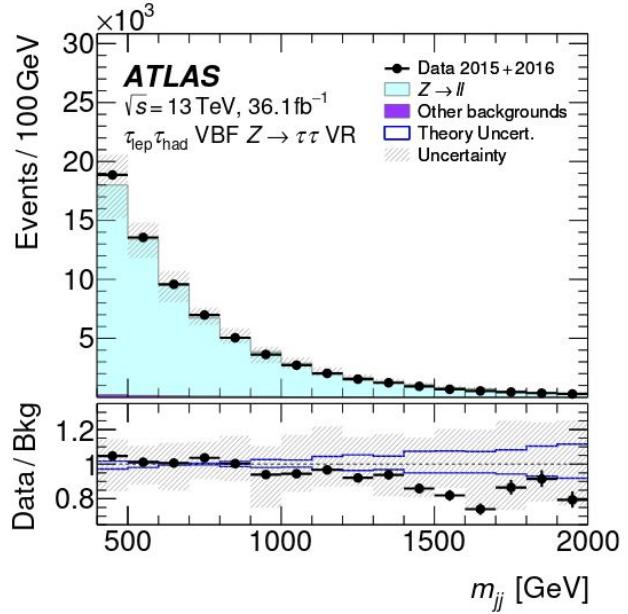
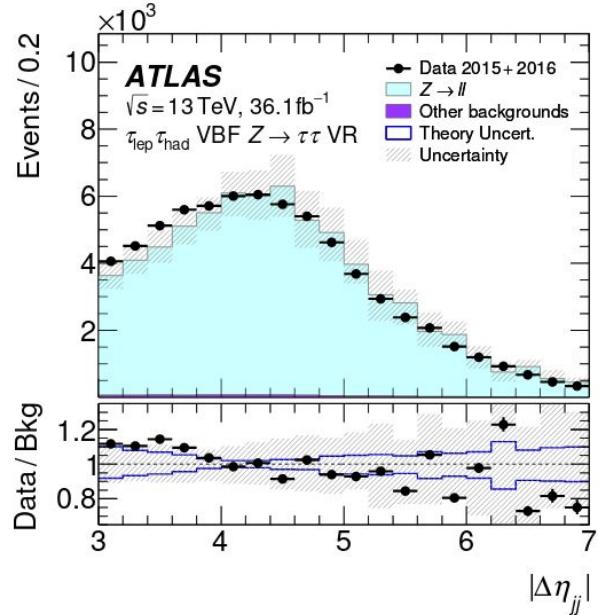
Background normalisation

Table 6: Normalization factors for backgrounds that have their normalization constrained using data in the fit, including all statistical and systematic uncertainties described in Section 7, but without uncertainties in total simulated cross sections extrapolated to the selected phase space. Systematic uncertainties are the dominant contribution to the normalization factor uncertainties. Also shown are the analysis channels to which the normalization factors are applied.

Background	Channel	Normalization factors	
		VBF	Boosted
$Z \rightarrow \ell\ell$ (CR)	$\tau_{\text{lep}}\tau_{\text{lep}}$	$0.88^{+0.34}_{-0.30}$	$1.27^{+0.30}_{-0.25}$
Top (CR)	$\tau_{\text{lep}}\tau_{\text{lep}}$	1.19 ± 0.09	1.07 ± 0.05
Top (CR)	$\tau_{\text{lep}}\tau_{\text{had}}$	$1.53^{+0.30}_{-0.27}$	1.13 ± 0.07
Fake- $\tau_{\text{had-vis}}$ (data-driven)	$\tau_{\text{had}}\tau_{\text{had}}$		1.12 ± 0.12
$Z \rightarrow \tau\tau$ (fit in each SR)	$\tau_{\text{lep}}\tau_{\text{lep}}, \tau_{\text{lep}}\tau_{\text{had}}, \tau_{\text{had}}\tau_{\text{had}}$	$1.04^{+0.10}_{-0.09}$	1.11 ± 0.05

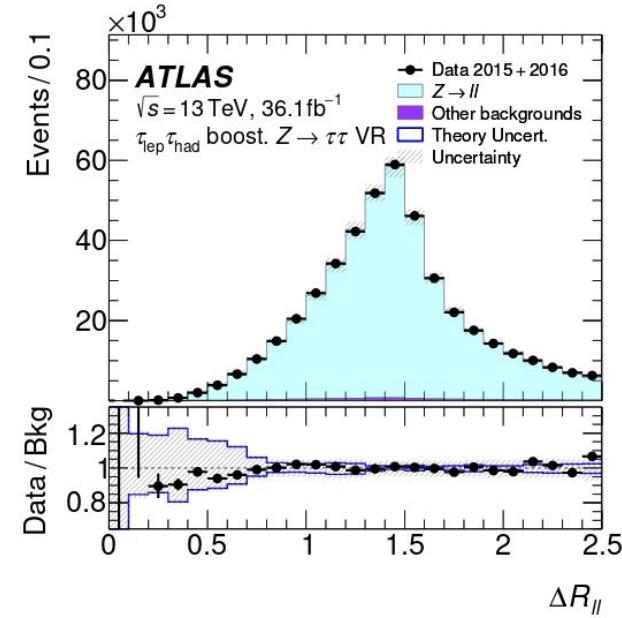
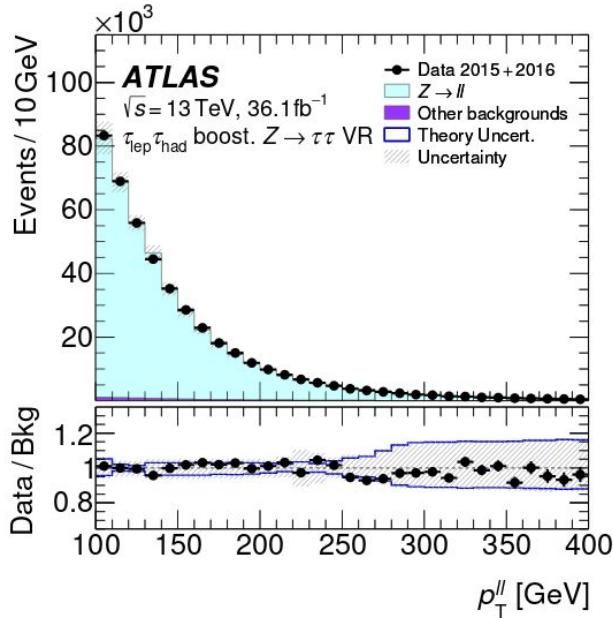
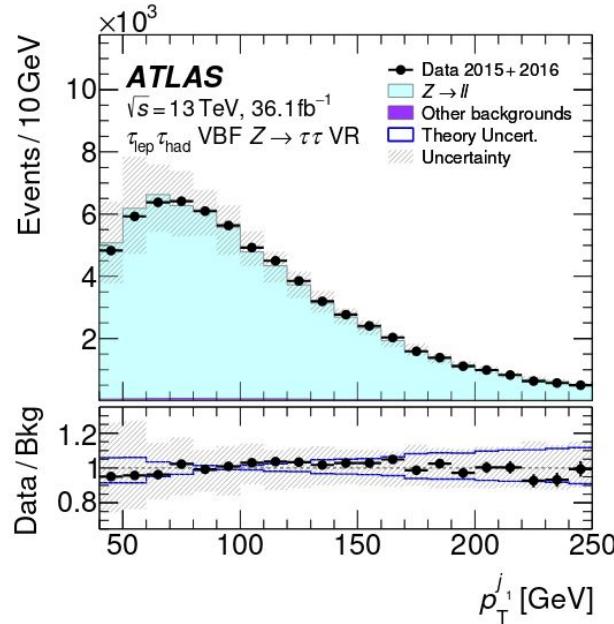
arXiv:1811.08856

Z validation 1



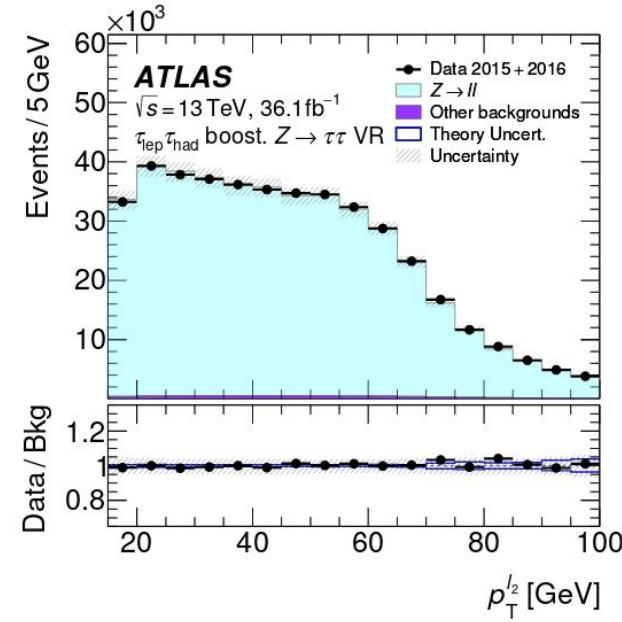
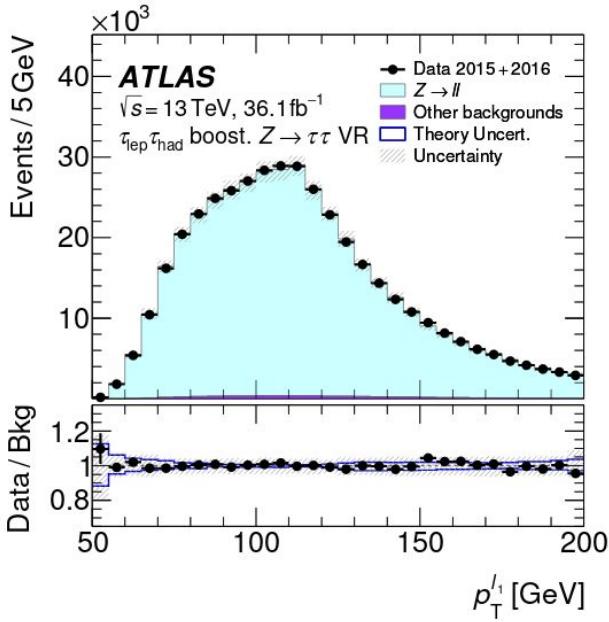
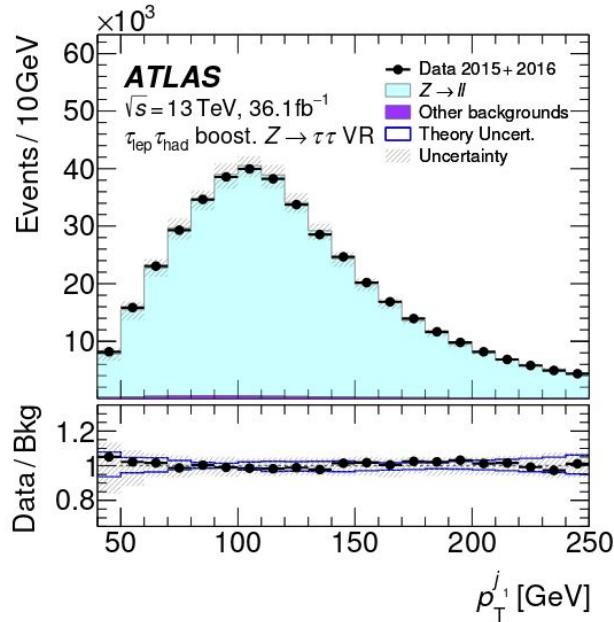
[HIGG-2017-07 \(high res plots etc\)](#)

Z validation 2



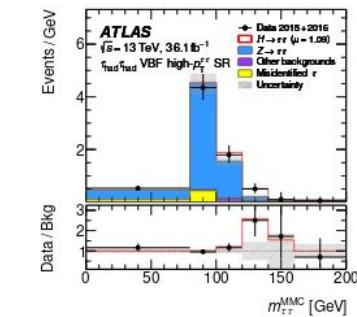
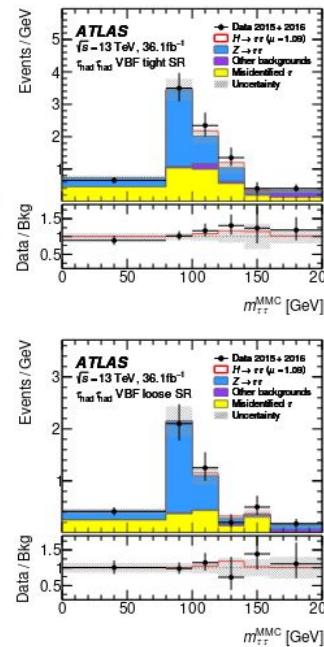
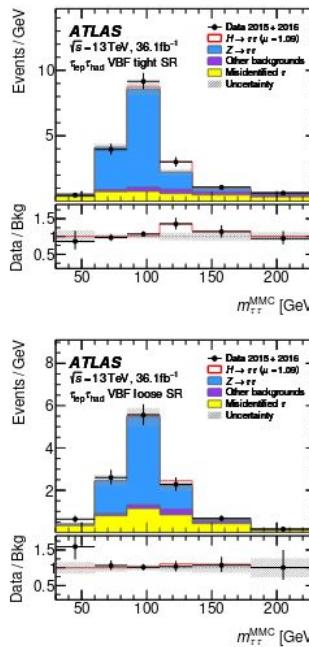
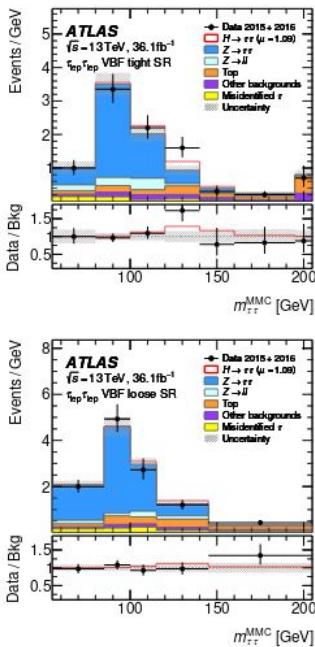
[HIGG-2017-07 \(high res plots etc\)](#)

Z validation 3



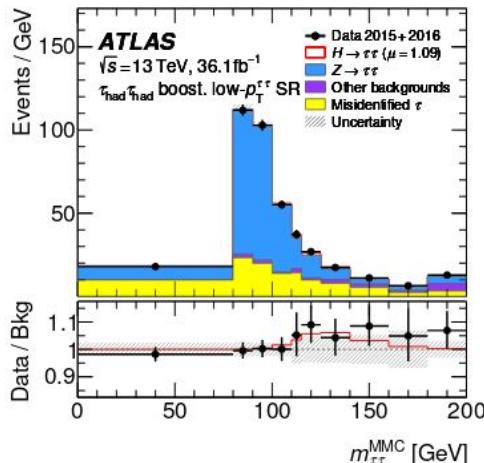
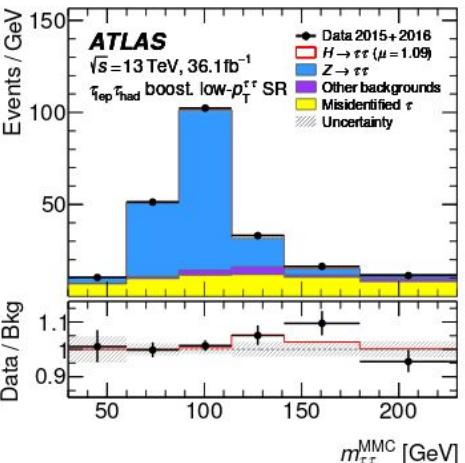
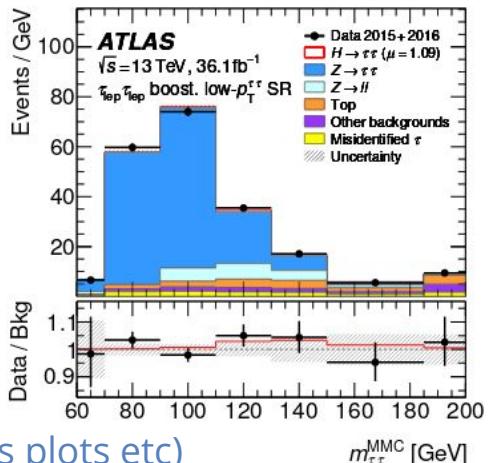
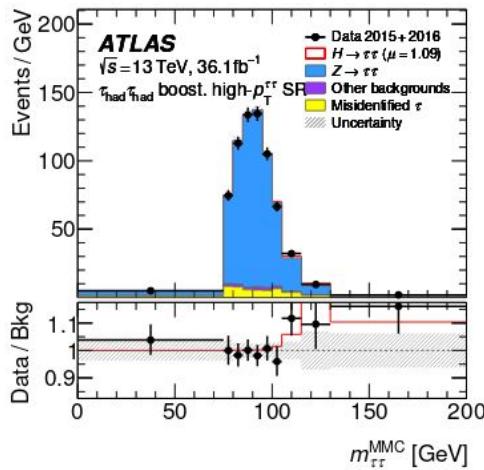
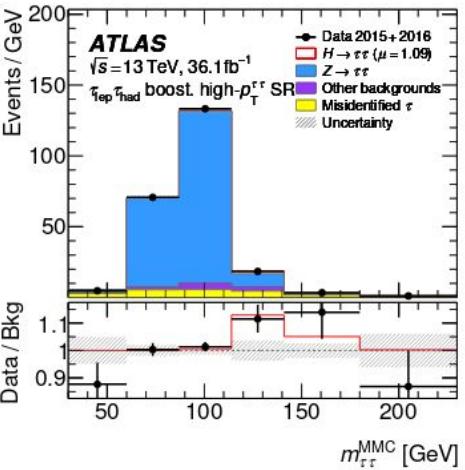
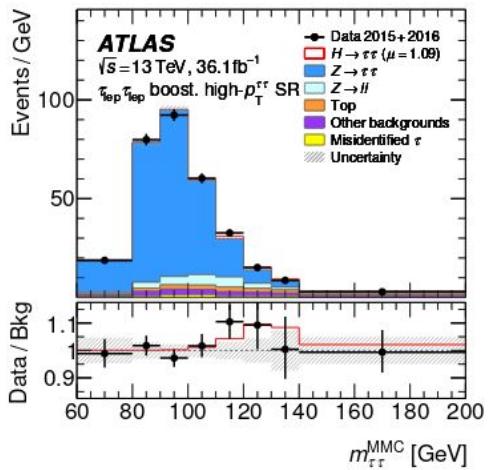
[HIGG-2017-07 \(high res plots etc\)](#)

SR plots VBF



[HIGG-2017-07 \(high res plots etc\)](#)

SR plots Boosted



[HIGG-2017-07 \(high res plots etc\)](#)

Free background normalisation parameters

$Z \rightarrow \ell\ell$

top quark pair

$Z \rightarrow \tau\tau$

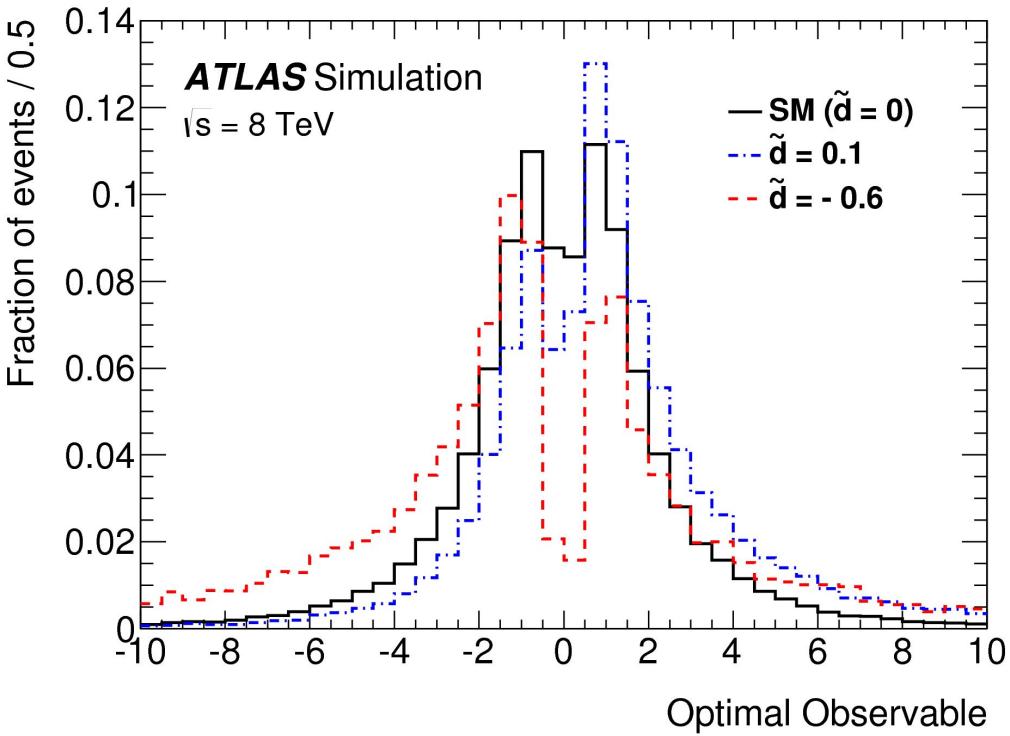
misidentified τ

	VBF			Boosted		
$\tau_{\text{lep}} \tau_{\text{lep}}$						
$\tau_{\text{lep}} \tau_{\text{had}}$						
$\tau_{\text{had}} \tau_{\text{ha}}$						
d						

+appropriate CRs for
each of $Z \rightarrow \ell\ell$ and
 top quark pair
parameters

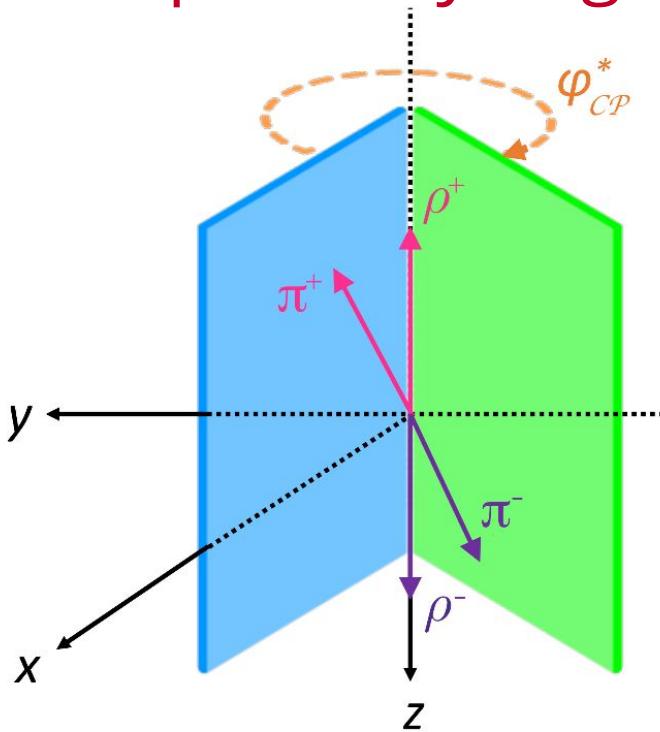
Optimal Observable

- calculated from LO ME (HAWK)
- inputs: reco H, jet 4-mom, parton x
- alternative hypothesis reweighting with HAWK
- SM hypothesis symmetric and $\langle O\bar{O} \rangle = 0$
- alternatives asymmetric and $\langle O\bar{O} \rangle \neq 0$
- backgrounds like SM



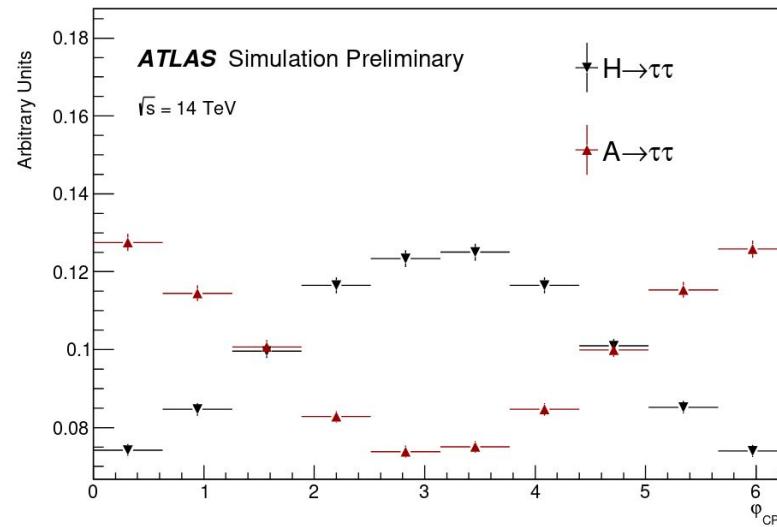
[HIGG-2015-06 \(high res plots etc\)](#)

Acoplanarity angle φ_{CP}^*



(a) φ_{CP}^* illustration

- exploit spin correlations in $\tau^\pm \rightarrow \rho^\pm \nu_\tau \rightarrow \pi^\pm \pi^0 \nu_\tau$
- alternative hypothesis reweighting with TauSpinner
- assume uniform background



(b) Generator level φ_{CP}^* distribution