Tau Polarisation Measurement in $Z/\gamma^* \to \tau\tau$ Decays at LHC

Benedict Winter on behalf of ATLAS and CMS

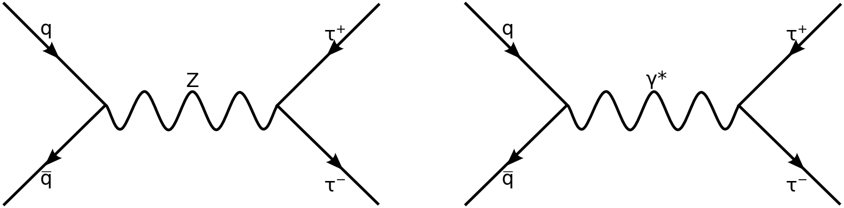
Amsterdam, September 25, 2018

Tau Polarisation around Z Boson Pole

Tau polarisation is

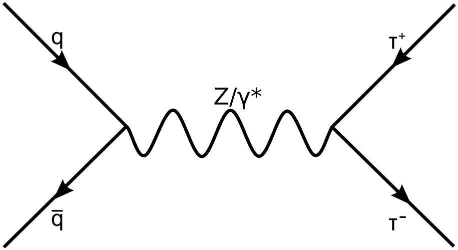
$$P_\tau = \frac{\sigma_{\text{right-handed}} - \sigma_{\text{left-handed}}}{\sigma_{\text{right-handed}} + \sigma_{\text{left-handed}}}$$

for the τ^- lepton.



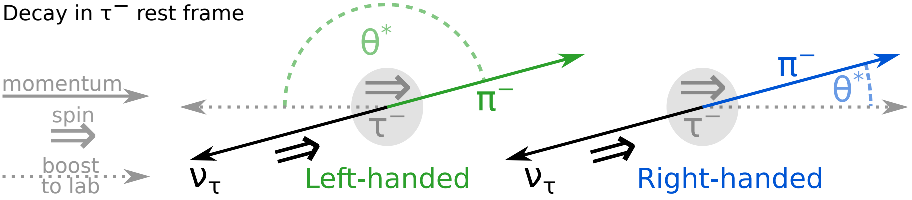
- Pure $Z \to \tau\tau$: $-P_\tau \approx A_\ell = \frac{2g_{V\ell}g_{A\ell}}{{g_{V\ell}}^2+{g_{A\ell}}^2} = 0.149 \approx 2 - 8\sin^2\theta_W$
- Pure $\gamma \to \tau\tau$: $P_\tau = 0$
- Z boson dominates for $m_{Z/\gamma^*} \approx m_Z$
- $P_\tau = -0.1517 \pm 0.0019$ within $66 < m_{Z/\gamma^*} < 116\,\text{GeV}$ predicted by Alpgen+Pythia6+Tauola

Measurement in $Z/\gamma^* \to \tau\tau$ decays at ATLAS [1709.03490]

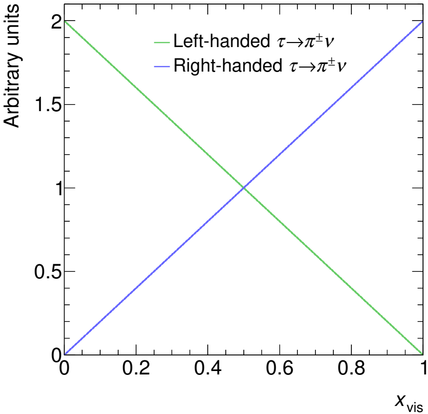


- Measure P_τ in a fiducial region and in 66 GeV $< m_{Z/\gamma^*} <$ 116 GeV range. Use 20.2 fb^{-1} dataset with $\sqrt{s} = 8$ TeV
- Z bosons produced via qqZ vertex $\Rightarrow$ complementary to precision measurements in ee collisions [hep-ex/0509008]
- Second P_τ measurement in hadron collisions. New experimental techniques
  - Evaluation of signal modelling uncertainties
  - Precise estimation of the significant backgrounds
- Previously found $P_\tau \in [-1.00, -0.91]$ with 95% credibility in $W \to \tau\nu$ using 24 pb^{-1} ATLAS data with $\sqrt{s} = 7$ TeV [1204.6720]

Tau Decays: $\tau \to \pi^{\pm}\nu$ (11%)



- Access spin via decays. 50 GeV taus fly ∼2.5 mm
- In τ^- rest frame for helicity λ_{τ^-}:
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta^*} \propto \frac{1}{2}(1 + \lambda_{\tau^-}\cos\theta^*)$$
- Lab distrib. of $x_{\text{vis}} = E^{\tau_{\text{had-vis}}}/E^{\tau}$:
$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}x_{\text{vis}}} = 1 + \lambda_{\tau^-}(2x_{\text{vis}} - 1)$$

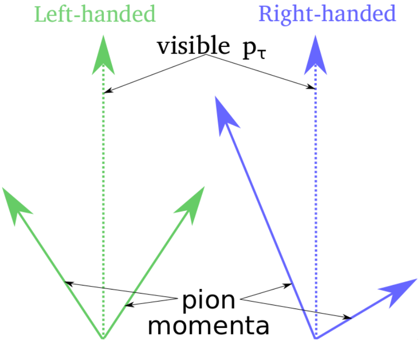


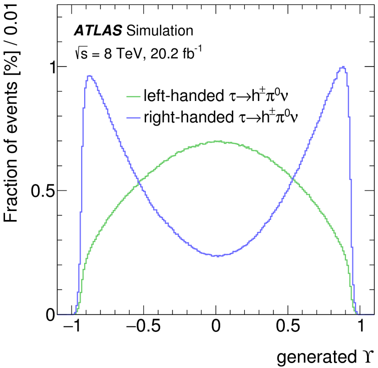
"Left-handed": $\lambda_{\tau^-} = -1$ or $\lambda_{\tau^+} = +1$

"Right-handed": $\lambda_{\tau^-} = +1$ or $\lambda_{\tau^+} = -1$

Tau Decays: $\tau \to h^{\pm}\pi^{0}\nu$ (26%)

Figure [1709.03490]



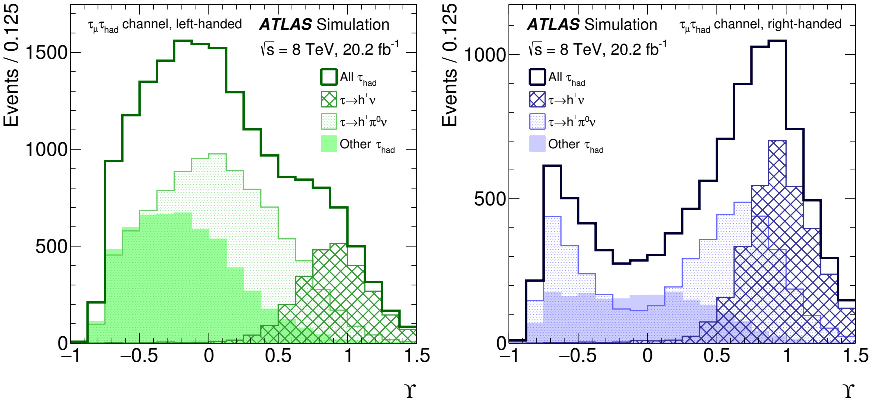


- Mostly $\tau \to \rho(\to \pi^{\pm}\pi^{0})\nu$ decays, where ρ meson has spin 1
- Left- (right-) handed: ρ with large x_{vis} are transversely (longitudinally) polarised, so pions have similar (different) momenta. Observable:

$$\Upsilon = \frac{E_{h^{\pm}} - E_{\pi^{0}}}{E_{h^{\pm}} + E_{\pi^{0}}}$$

Reconstructed Υ Observable

Figures [1709.03490]

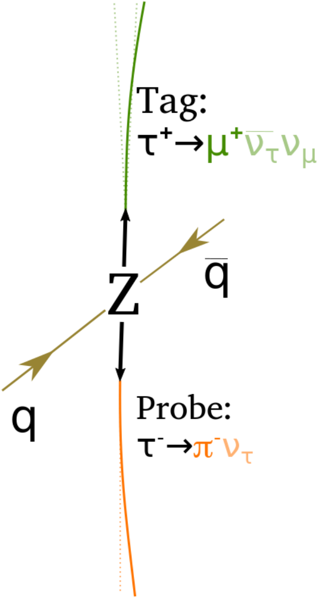


ATLAS Run 1: decay mode and π^0 momenta not reconstructed $\Rightarrow$ Use

$$\Upsilon = \frac{E_{h^\pm} - E_{\pi^0}}{E_{h^\pm} + E_{\pi^0}} \approx \frac{2 \cdot p_T^{h^\pm}}{p_T^{\tau_{\text{had-vis}}}} - 1,$$

where $h^\pm$ denotes $\pi^\pm$ and $K^\pm$. Select taus with one $h^\pm$

Signal Signature and Event Selection



Lepton selection:

- Single electron or muon trigger
- $p_T^{\tau_{\text{lep}}} > 26$ GeV, $|\eta^{\tau_{\text{lep}}}| < 2.5$
- Pass identification and isolation

τ_{had} selection:

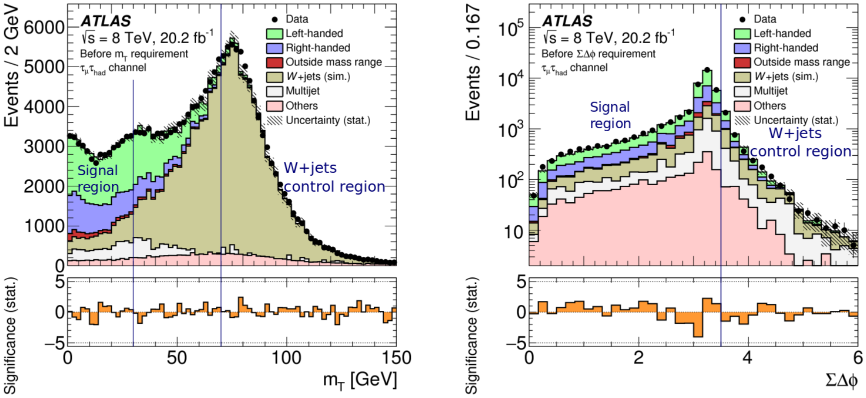
- $p_T^{\tau_{\text{had-vis}}} > 20$ GeV, $|\eta^{\tau_{\text{had-vis}}}| < 2.5$
- Pass medium identification
- Single-prong

Event topology:

- Opposite lepton and τ_{had} electric charges
- $m_T < 30$ GeV
- $\sum \Delta\phi < 3.5$
- $40 < m_{\text{vis}} < 85$ GeV
- Separate τ_e–τ_{had} and τ_μ–τ_{had} channels

Suppression of $W \to \ell\nu$ Background

Figures [1709.03490]

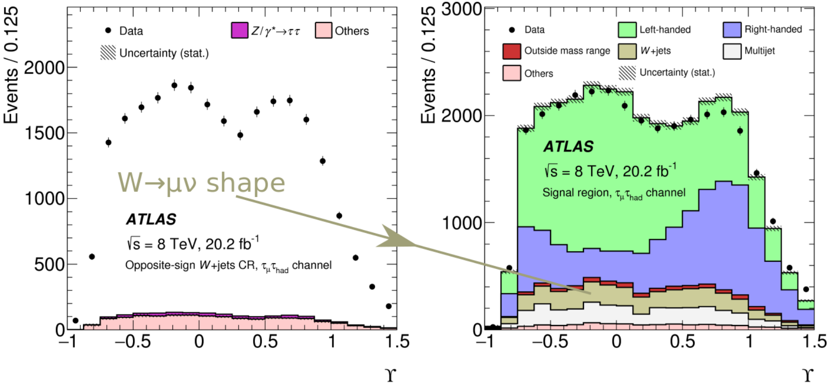


$$m_T = \sqrt{2 \cdot p_T^{\text{lepton}} \cdot E_T^{\text{miss}} \cdot \left(1 - \cos\Delta\phi\left(p_T^{\text{lepton}}, E_T^{\text{miss}}\right)\right)}$$

$$\sum \Delta\phi = \left|\Delta\phi(p_T^{\text{lepton}}, E_T^{\text{miss}})\right| + \left|\Delta\phi\left(p_T^{\tau_{\text{had-vis}}}, E_T^{\text{miss}}\right)\right|$$

W+jets Background Estimate ▸ Figures [1709.03490]

W+jets control region | Signal region

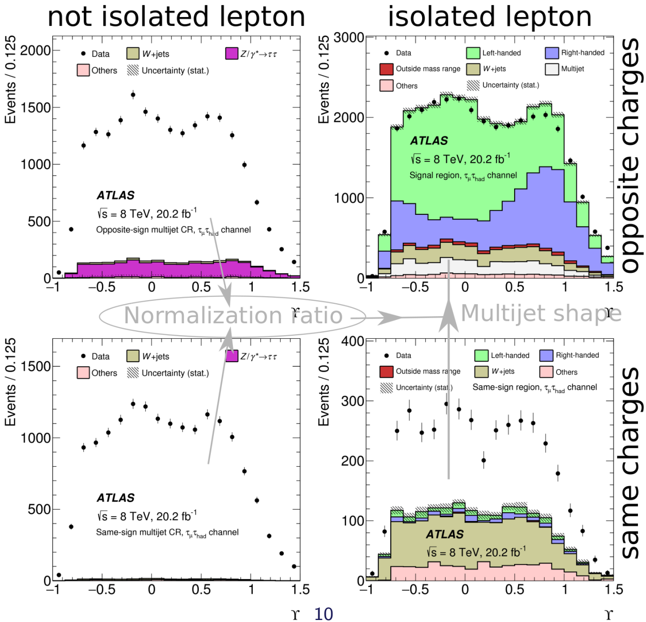


- W+jets control region: $m_{\mathrm{T}} > 70$ GeV and $\sum \Delta\phi \geq 3.5$
- Shape: from data in W+jets control region with small correction
- Normalisation: scale using simulation

$$N^{\text{signal region}}_{\text{estimated}} = N^{W+\text{jets CR}}_{\text{observed}} \cdot \frac{N^{\text{signal region}}_{\text{simulated}}}{N^{W+\text{jets CR}}_{\text{simulated}}}$$

Multijet Background Estimate

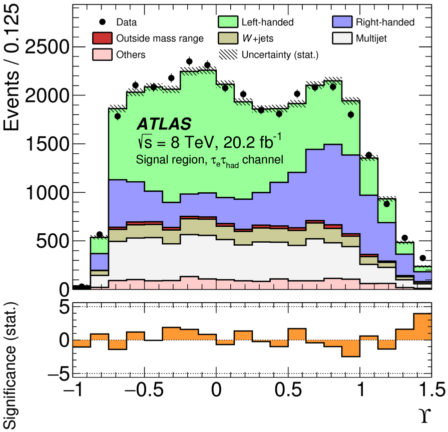
Figures [1709.03490]



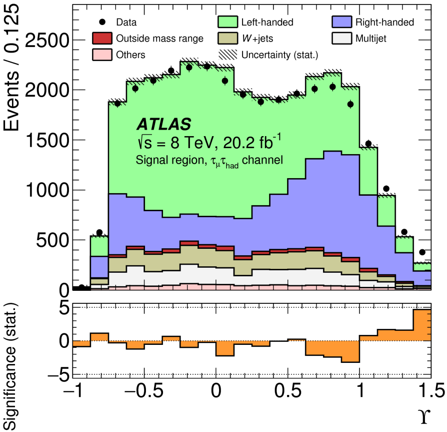
Expected Υ Distributions in Signal Region

Figures [1709.03490]

τ_e–τ_{had} channel



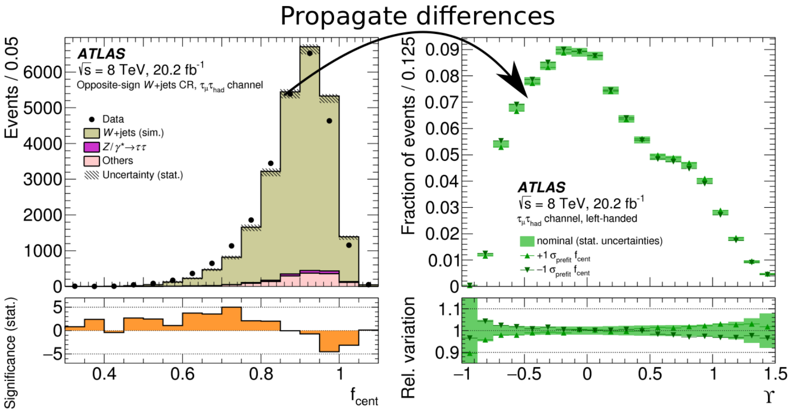
τ_μ–τ_{had} channel



- Tau polarisation shown as predicted by simulation
- Signal purity: 68% (τ_e–τ_{had} channel), 84% (τ_μ–τ_{had} channel)
- Minor $Z/\gamma^* \to \ell\ell$ and top pair backgrounds from simulation

Example Systematic: τ_{had} Identification

Figures [1709.03490]



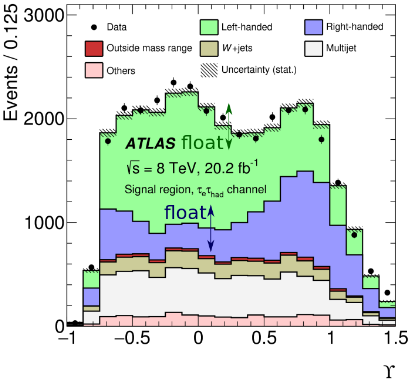
Impact of tau identification (ID) on shape of Υ distribution:

- Estimate uncertainties in each τ_{had} ID input variable in W+jets CR
- Propagate differences to signal in signal region and consider shape variations as uncertainties

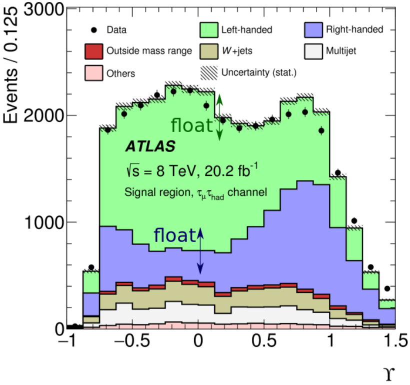
Extraction of Tau Polarisation

Figures [1709.03490]

τ_e–τ_{had} channel



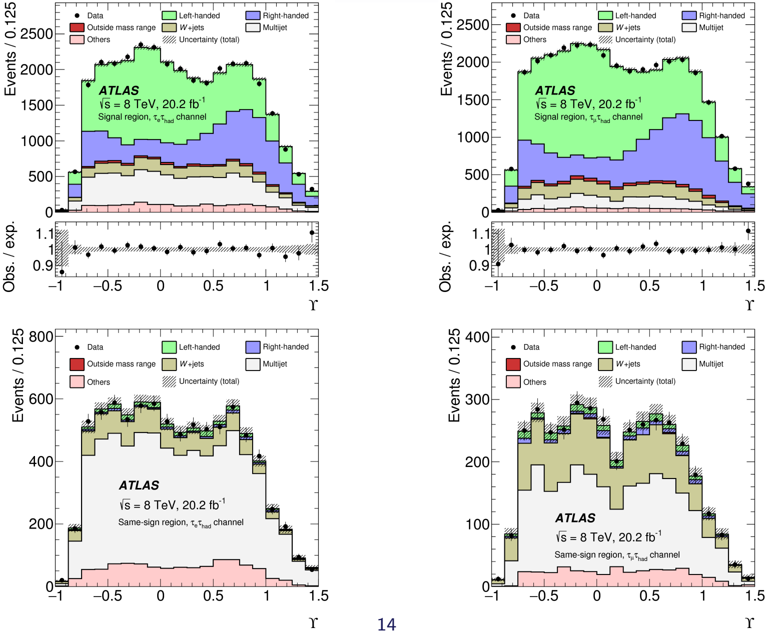
τ_μ–τ_{had} channel



- Extended binned maximum likelihood fit
- Simultaneously fit signal and same-sign regions in both channels
- Polarisation extracted from relative normalisation of left- and right-handed signal templates
- Nuisance parameters control template variations within uncertainties

Post Fit ϒ Distributions

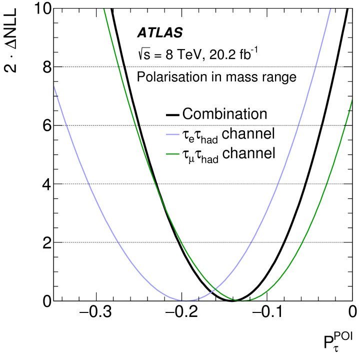
Figures [1709.03490]

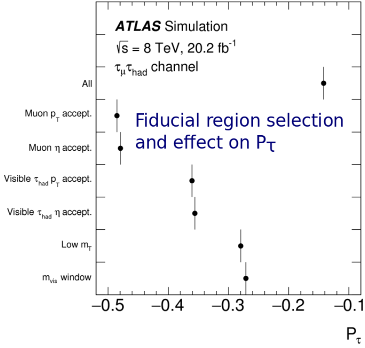


Results

Table and Figure [1709.03490]

Channel	P_τ in mass-selected region	P_τ in fiducial region
τ_e–τ_{had}	-0.20 ± 0.02 (stat) $\pm$ 0.05 (syst)	-0.33 ± 0.03 (stat) $\pm$ 0.05 (syst)
τ_μ–τ_{had}	-0.13 ± 0.02 (stat) $\pm$ 0.05 (syst)	-0.26 ± 0.02 (stat) $\pm$ 0.05 (syst)
Combination	-0.14 ± 0.02 (stat) $\pm$ 0.04 (syst)	-0.27 ± 0.02 (stat) $\pm$ 0.04 (syst)
Prediction	-0.1517 ± 0.0019	-0.270 ± 0.006

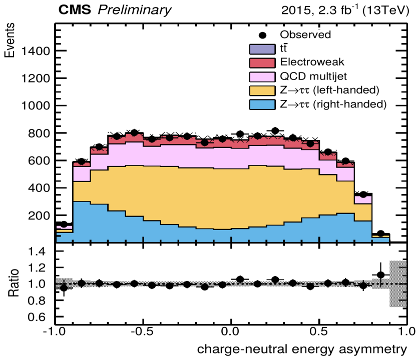




- Measurement of $\sin^2\theta_W$ would require correction for $\gamma \to \tau\tau$ contribution and interference

CMS: Study with Single-Prong τ_{had} Decays

▸ Figure CMS DP 2016/60



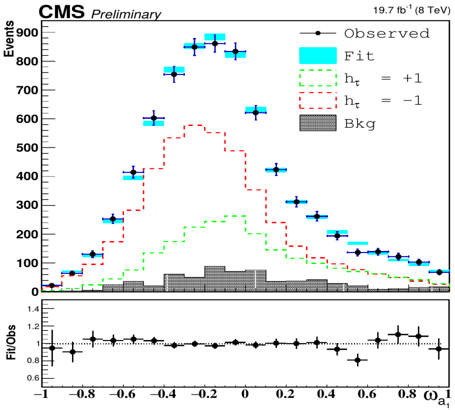
- Select $Z/\gamma^* \to \tau\tau$ decays with one $\tau \to \mu\nu\nu$ decay and one single-prong τ_{had} decay from $2.3\,\text{fb}^{-1}$ dataset with $\sqrt{s} = 13\,\text{TeV}$
- Require reconstructed π^0 in τ_{had} decay. Reconstruct

$$\Upsilon = \frac{E_{h^\pm} - E_{\pi^0}}{E_{h^\pm} + E_{\pi^0}}$$

- Stat-only fit: $P_\tau = -0.336 \pm 0.037$ in signal region (predict: -0.33)

CMS: Study with Three-Prong τ_{had} Decays

▸ Figure CMS DP 2016/60



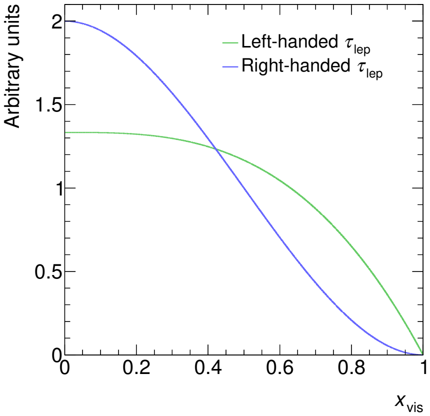
- Two thirds of three-prong decays proceed via $a_1 \to \rho\pi \to \pi\pi\pi$
- Construct so-called optimal observable ω_{a_1} from three τ_{had} decay angles assuming $m_{Z/\gamma^*} = m_Z$ and $p_{\text{T},Z} = 0$
- Stat-only fit to 19.7 fb^{-1} data with $\sqrt{s} = 8$ TeV yields $P_\tau = -0.355 \pm 0.064$ in signal region (predict: -0.32)

Conclusions

- ATLAS measured tau polarisation in $Z/\gamma^* \to \tau\tau$ decays using single-prong τ_{had} decays as spin analysers. Precision: 0.05
- CMS performed advanced performance studies using single- and three-prong τ_{had} decays and decay mode identification

Great prospects for further measurements in $Z/\gamma^* \to \tau\tau$ and other processes

Backup: Tau Decays: $\tau \to \ell\nu\nu$ (35%)



- Three-body decay into left-handed fermions
- Unobservable neutrinos reduce sensitivity of x_{vis} w.r.t. $\tau \to \pi^{\pm}\nu$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}x_{\text{vis}}} = \frac{G_F^2 m_\tau^5}{192\pi^3}\left(\frac{5}{3} - 3x_{\text{vis}}^2 + \frac{4}{3}x_{\text{vis}}^3 - \lambda_\tau\left(-\frac{1}{3} + 3x_{\text{vis}}^2 - \frac{8}{3}x_{\text{vis}}^3\right)\right)$$

Backup: Event Generators

Table [1709.03490]

Sample	Event generator	PDF	UE tune
$(Z/\gamma^* \to \tau\tau)$ + jets	ALPGEN 2.14 [3] + PYTHIA6.427 [4]	CTEQ6L1 [10]	Perugia2011C [11]
$(Z/\gamma^* \to \tau\tau)$ + jets	PYTHIA 8.160 [20]	CTEQ6L1	AU2 [21]
$(Z/\gamma^* \to \tau\tau)$ + jets	POWHEG r1556 [22,23,24] + PYTHIA 8.160	CT10 [25]	AUET2 [31]
$(Z/\gamma^* \to \tau\tau)$ + jets	ALPGEN 2.14 + HERWIG 6.5/JIMMY 4.3 [26,27]	CTEQ6L1	Perugia2011C
Top pairs + jets	POWHEG r2129 + PYTHIA 6.426	CT10	AUET2
$(W \to e\nu)$ + jets	ALPGEN 2.14 + PYTHIA 6.427	CTEQ6L1	Perugia2011C
$(W \to \mu\nu)$ + jets	ALPGEN 2.14 + PYTHIA 6.427	CTEQ6L1	Perugia2011C
$(W \to \tau\nu)$ + jets	ALPGEN 2.14 + PYTHIA 6.427	CTEQ6L1	Perugia2011C
$(Z/\gamma^* \to ee)$ + jets	ALPGEN 2.14 + PYTHIA 6.427	CTEQ6L1	Perugia2011C
$(Z/\gamma^* \to \mu\mu)$ + jets	ALPGEN 2.14 + PYTHIA 6.427	CTEQ6L1	Perugia2011C

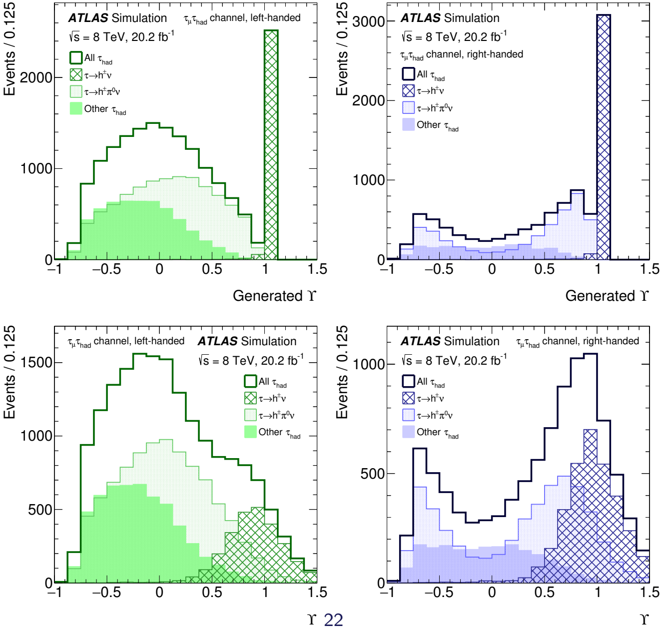
Backup: Event Yields

Table [1709.03490]

Process	τ_e–τ_{had} channel	τ_μ–τ_{had} channel
Data	32243	32347
Total expected	$32000\ ^{+1600}_{-1600}$	$33000\ ^{+1800}_{-1800}$
Left-handed	$13800\ ^{+1100}_{-1100}$	$17000\ ^{+1400}_{-1300}$
Right-handed	$7800\ ^{+600}_{-600}$	$9600\ ^{+700}_{-700}$
Outside mass-selected region	$430\ ^{+40}_{-40}$	$550\ ^{+40}_{-40}$
W+jets	$2240\ ^{+260}_{-240}$	$2600\ ^{+210}_{-220}$
Multijet	$6200\ ^{+600}_{-600}$	$2400\ ^{+270}_{-300}$
Top pair	$360\ ^{+40}_{-40}$	$390\ ^{+40}_{-40}$
$(Z/\gamma^* \to \ell\ell)$+jets	$1210\ ^{+140}_{-140}$	$360\ ^{+50}_{-40}$

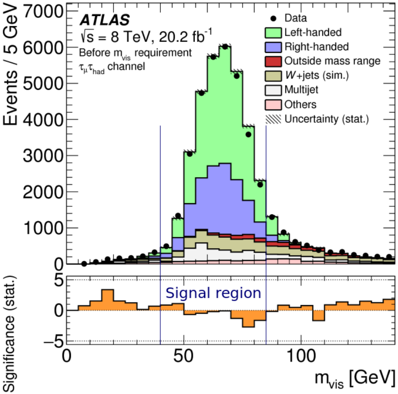
Backup: Generated and Reco. Υ Distributions

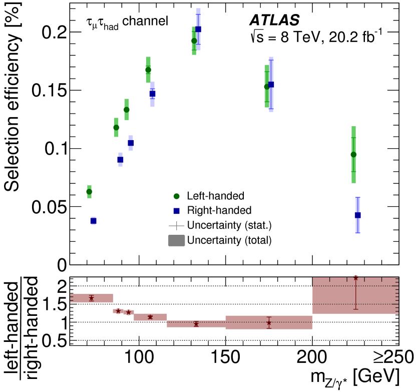
▸ Figures [1709.03490]



Backup: The m_{vis} Requirement

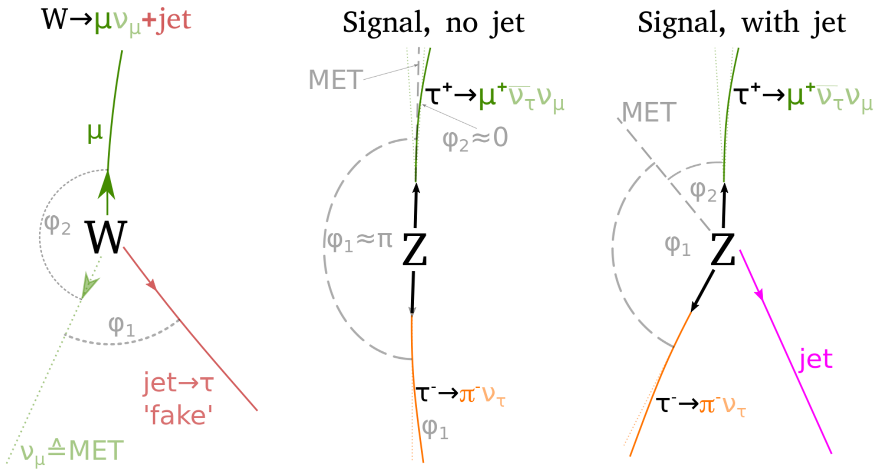
Figures [1709.03490]





- Visible mass: $m_{\text{vis}} = \sqrt{\left(p^{\text{lepton}} + p^{\tau_{\text{had-vis}}}\right)^2}$
- Cut eliminates interesting events with true $m_{Z/\gamma^*} \gg m_Z$. But would need dedicated measurement anyway

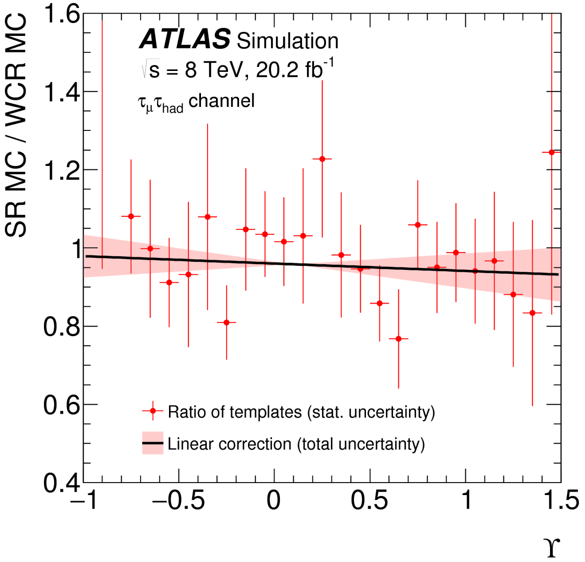
Backup: Suppression of $W \to \ell\nu$ Background



- Definition: $\sum \Delta\varphi = \varphi_1 + \varphi_2$,
- For signal: $\sum \Delta\varphi \lesssim \pi$. For background: $\sum \Delta\varphi > \pi$

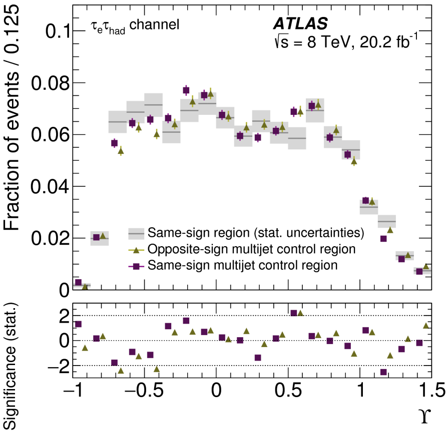
Backup: Shape Correction in W+jets Estimate

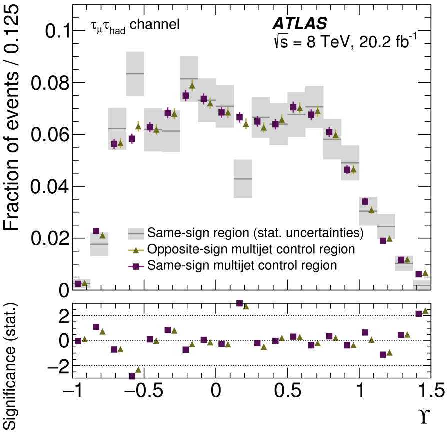
Figure [1709.03490]



Backup: Opposite- and Same-Sign Shape Differences

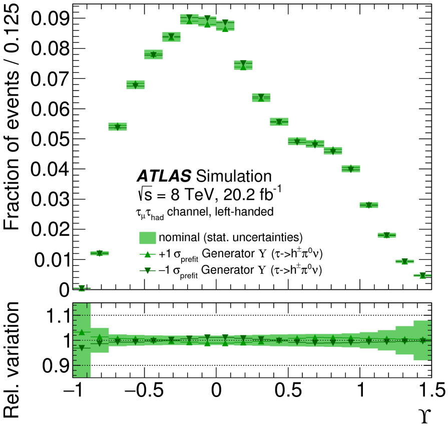
Figures [1709.03490]

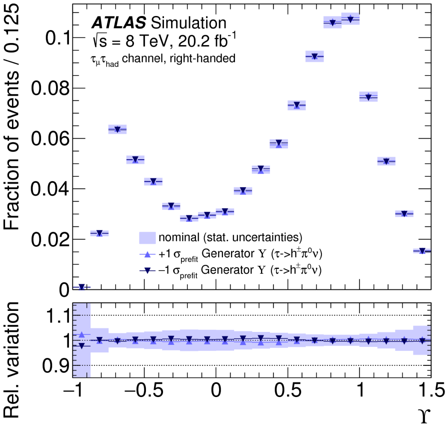




Systematics: Modelling of Signal Process

Figures [1709.03490]

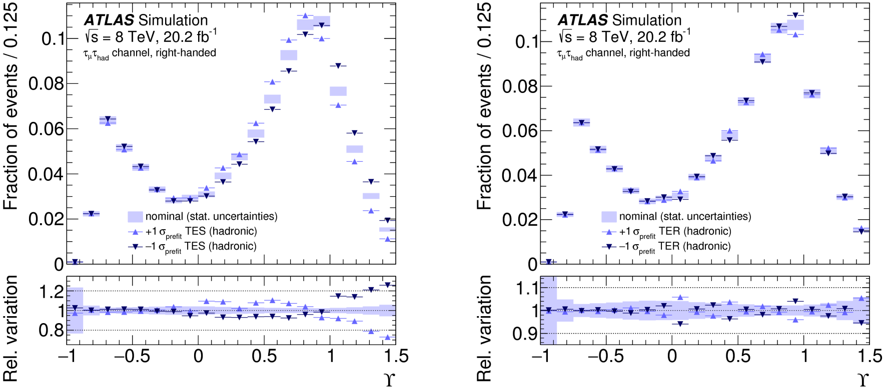




- Compare nominal Alpgen+Pythia6 to Pythia8 and Powheg+Pythia8
- Reweigh various truth level distributions

Systematics: Tau Energy Reconstruction

▸ Figures [1709.03490]



- Momentum reconstruction directly enters $\Upsilon = \frac{2 \cdot p_T^{\text{track}}}{p_T^{\tau_{\text{had-vis}}}} - 1$,
- Energy scale (TES) and resolution (TER) uncertainties estimated separately for hadrons ($\pi^{\pm}$) and photons (from $\pi^0 \to \gamma\gamma$ decays)

Backup: Systematic Uncertainties

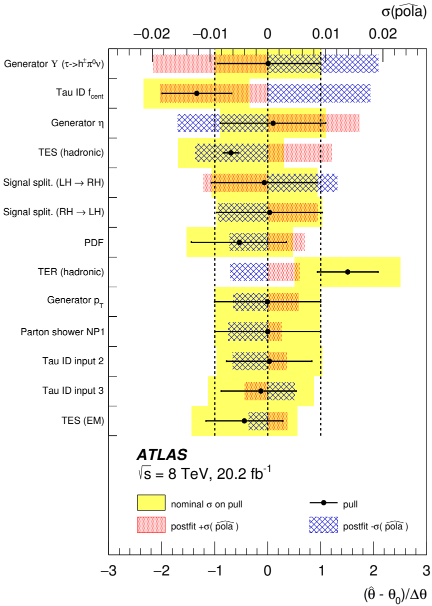
Tables [1709.03490]

Source of uncertainty	Number of parameters	Constraint	Steer variation of
Multijet estimate	40	None	one bin each
MC statistical	40	Poissonian	one bin each
Modelling of signal process	3	Gaussian	shape and normalisation
τ_{had} identification	5	Gaussian	shape or normalisation
Signal sample splitting	2	Gaussian	shape and normalisation
TES and TER	6	Gaussian	shape and normalisation
PDF	1	Gaussian	shape and normalisation
W+jets shape	2	Gaussian	shape
Other	34 or 36	Gaussian	normalisation

Source of uncertainty	σ_{P_τ} in mass-selected region	σ_{P_τ} in fiducial region
Modelling of signal process	± 0.026	± 0.022
τ_{had} identification	± 0.020	± 0.024
MC statistical	± 0.016	± 0.019
Signal sample splitting	± 0.015	± 0.015
TES and TER	± 0.015	± 0.019
Multijet estimate	± 0.013	± 0.013
PDF	± 0.007	± 0.005
W+jets shape	± 0.002	± 0.003
Other	± 0.008	± 0.003
Total systematic uncertainty	± 0.040	± 0.039
Statistical uncertainty	± 0.015	± 0.016

Backup: Post Fit NP Values and Uncertainties

▸ Figure [1709.03490]



- ϒ very sensitive to TES → TES parameters are constrained
- TER not measured before and pulled noticeably
- Other pulled parameters are analysis specific as well

Backup: Signature of $\tau \to \pi^{\pm}\pi^{0}\nu$ Decay in ATLAS Calorimeter