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[https://doi.org/10.1007/jhep10\(2025\)054](https://doi.org/10.1007/jhep10(2025)054)

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RECEIVED: March 26, 2025

ACCEPTED: September 8, 2025

PUBLISHED: October 7, 2025

A measurement of the high-mass $\tau\bar{\tau}$ production cross-section at $\sqrt{s} = 13$ TeV with the ATLAS detector and constraints on new particles and couplings



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ABSTRACT: The production cross-section of high-mass τ -lepton pairs is measured as a function of the dilepton visible invariant mass, using 140 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collision data recorded with the ATLAS detector at the Large Hadron Collider. The measurement agrees with the predictions of the Standard Model. A fit to the invariant mass distribution is performed as a function of b -jet multiplicity, to constrain the non-resonant production of new particles described by an effective field theory or in models containing leptoquarks or Z' bosons that couple preferentially to third-generation fermions. The constraints on new particles improve on previous results, and the constraints on effective operators include those affecting the anomalous magnetic moment of the τ -lepton.

KEYWORDS: Beyond Standard Model, Hadron-Hadron Scattering

ARXIV EPRINT: [2503.19836](https://arxiv.org/abs/2503.19836)

Contents

1	Introduction	1
2	ATLAS detector and data set	2
3	Object reconstruction	3
4	Modelling	4
4.1	Monte Carlo samples	5
4.2	Misreconstructed τ_{had} background	7
5	Measurement of the inclusive $\tau_{\text{had}}\tau_{\text{had}}$ cross-section	9
5.1	Definition of the measured final state	9
5.2	Correction for detector effects	9
5.3	Results	12
6	Search for new non-resonant interactions	12
6.1	SM effective field theory	13
6.2	Leptoquark models	14
6.3	Z' boson model	16
6.4	Fit frameworks	16
6.5	Results	17
7	Conclusion	22
	The ATLAS collaboration	33

1 Introduction

The study of Drell-Yan production of charged-lepton pairs resulted in the historic discoveries of the J/ψ [1, 2] and Υ [3] mesons, and of the Z boson [4, 5]. Further studies have provided precise measurements of the weak mixing angle [6–8] and constraints on parton distribution functions [9–12]. At high invariant mass, Drell-Yan production probes a variety of possible new interactions including the production or exchange of Z' bosons [13, 14], leptoquarks [15], and additional Higgs bosons [16]. There are well-motivated scenarios for these particles to have enhanced couplings to third-generation fermions [17], making Drell-Yan production in the $\tau\bar{\tau}$ final state a promising probe for new physics. For example, measurements of B -hadron decays to $D^{(*)}\tau\nu$ show increased rates relative to the corresponding decays to lighter leptons [18–26]. This could be explained by the presence of a leptoquark or Z' boson that preferentially couples to third-generation fermions and would affect $\tau\bar{\tau}$ production at high invariant mass.

Prior studies of $pp \rightarrow \tau\bar{\tau}$ production have probed the Z boson resonance [27–29], while studies of light leptons have extended to high invariant mass [10, 30–34]. Searches for new particles have probed the high-mass region for both resonant and non-resonant production

of τ -lepton pairs [33, 35–38]. This paper presents the first measurement of the inclusive $\tau\bar{\tau}$ fiducial cross-section as a function of visible invariant mass, along with a search for new states through non-resonant interactions. These interactions include generic four-fermion interactions and $\tau\tau\gamma$ interactions that affect the anomalous magnetic moment of the τ -lepton. The analysis is performed using the hadronic decays of the τ -leptons since the Drell-Yan purity is lower when there is one or more leptonic decay.

To improve sensitivity to third-generation couplings, non-resonant interactions are probed in bins of b -jet multiplicity. A b -quark from the proton participating in the hard interaction will frequently have an associated $\bar{b}$ quark with substantial momentum. The maximum sensitivity to new third-generation interactions is observed in final states with one b -jet. The fit in bins of b -jet multiplicity constrains significant backgrounds, improving the sensitivity to new processes. For interactions beyond the SM (BSM), the BSM-only process is considered along with its interference with the SM production of τ -lepton pairs. The interference contribution is found to significantly affect signal constraints, and has not been included in previous non-resonant searches in this final state [37, 38].

This paper is organized as follows. Section 2 describes the ATLAS detector and the data samples. Section 3 gives a brief overview of the reconstruction of physics objects, focusing primarily on the reconstruction and identification of hadronic τ -lepton decays. A detailed discussion of the data modelling follows in section 4, covering both the Monte Carlo samples used in the analysis and the data-driven estimate of the misreconstructed τ -lepton background. The results of the $\tau\bar{\tau}$ cross-section measurement are presented in section 5, and those of the non-resonant search in section 6. Conclusions are provided in section 7.

2 ATLAS detector and data set

The ATLAS experiment [39] at the Large Hadron Collider (LHC) [40] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.¹ It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The MS surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the

¹ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z -axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$. Momentum projected onto the transverse plane is denoted p_T .

toroids ranges between 2.0 and 6.0 T m across most of the detector. The MS includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$.

A two-level trigger system is used to select events [41]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [42] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The data set was collected between 2015 and 2018, during the LHC Run-2 production of $\sqrt{s} = 13$ TeV pp collisions, and corresponds to an integrated luminosity of 140 fb^{-1} with an uncertainty of 0.83% [43]. The LUCID-2 detector [44] is used for the primary luminosity measurements, which are complemented by measurements using the inner detector and calorimeters. Events are included from runs with fully operational tracking detectors and calorimetry [45], and were primarily collected with a trigger requiring a hadronically decaying τ -lepton with $p_T > 80$ GeV and another with $p_T > 60$ GeV in the software-based trigger. A single- τ trigger contributes significantly to the efficiency at high invariant mass. To ensure a high trigger efficiency the offline selection requires the highest p_T τ -lepton to have $p_T > 90$ GeV. The selection yields a total of 6679 events. Additional validation data sets were primarily collected with a trigger requiring a single electron or muon with $p_T > 28$ GeV. Events from these triggers, along with those from a single-jet trigger, are used in the background estimation [46].

3 Object reconstruction

This analysis uses events with two reconstructed τ -leptons decaying into hadrons (τ_{had}). Validation of the modelling is performed using events with one τ_{had} and one charged lepton (e or μ). The data are separated into bins of b -jet multiplicity to maximize sensitivity to interactions involving b -quarks. Standard ATLAS procedures are applied for the reconstruction and calibration of these objects.

Hadronic τ -lepton decays produce a neutrino and visible decay products, typically one or three charged pions and up to two neutral pions. The reconstruction of the τ_{had} object is seeded by jets reconstructed using the anti- k_t algorithm [47] with a radius parameter of $R = 0.4$. Reconstructed tracks are then matched to τ_{had} candidates. These candidates must have one or three associated tracks whose charge sum is ± 1 , and must have $|\eta| < 2.47$ excluding the transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$) due to the large amount of material in front of the first active layer. In order to separate the τ_{had} candidates produced by hadronic τ -lepton decays from those produced by jets initiated by quarks or gluons, a recurrent neural-network identification algorithm (RNN) [48] is used. This algorithm uses information from reconstructed charged-particle tracks and calorimeter energy clusters, together with high-level discriminating variables. The τ_{had} objects are required to fulfill the ‘Tight’ identification criterion. A separate discriminant (‘eBDT’) [49] is constructed to reject backgrounds originating from electrons misidentified as τ_{had} , arising mostly from $Z \rightarrow ee$ events in this analysis. In events with an identified electron, the τ_{had} object is required to pass the ‘Loose’ working point of the eBDT algorithm. Systematic uncertainties

in the τ_{had} reconstruction vary with p_T and range from 2–6% for the RNN and 1–2% for the eBDT. The τ_{had} energy scale is studied using $Z \rightarrow \tau\tau$ decays in events with one muon and one τ_{had} , and has an uncertainty of 1–4% [50].

Jets are reconstructed using the anti- k_t algorithm as implemented in FastJet [51] with a jet radius parameter $R = 0.4$. The inputs to this algorithm are particle flow (PFlow) objects [52], which combine measurements from the ATLAS inner detector and calorimeters [53] to improve the jet energy resolution and increase the jet reconstruction efficiency, especially at low jet p_T . A jet vertex tagger (JVT) [54] is used to remove jets with $p_T < 60$ GeV and $|\eta| < 2.5$ that are identified as not being associated with the event’s primary vertex, defined as the vertex with the highest $\sum p_T^2$ of associated tracks. Similarly, pile-up jets in the forward region are suppressed with a forward JVT [55] algorithm, which exploits jet shapes and topological jet correlations in pile-up interactions and is applied to all jets with $p_T < 60$ GeV and $|\eta| > 2.5$. Calibrations are applied to the jet energy scale (JES) and jet energy resolution (JER), which include components derived both from simulation and in situ measurements [56]. Systematic uncertainties in the JES and JER are evaluated using a series of simulation-based techniques and in-situ measurements.

Jets originating from b -quarks are identified using the DL1r b -tagging algorithm [57] and are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. Operating points are defined by a single threshold on the discriminant output distribution and are chosen to provide a specific b -jet efficiency on an inclusive $t\bar{t}$ Monte Carlo sample [58]. The 77% working point is used to select b -jets. Correction factors are applied to the simulated event samples to compensate for differences between data and simulation in the b -tagging efficiency for b , c and light-quark jets. The correction for b -jets is derived from $t\bar{t}$ events with final states containing two leptons, and the corrections are consistent with unity with uncertainties at the level of a few percent over most of the jet p_T range.

Electrons are reconstructed from topological clusters of energy deposits in the electromagnetic calorimeter, matched to a track reconstructed in the ID. They are required to satisfy the ‘Medium’ identification criteria [59], to have $p_T > 7$ GeV, and to be in the fiducial volume of the ID and the high-granularity electromagnetic calorimeters, $|\eta| < 2.47$, with the exclusion of the LAr barrel-endcap transition region $1.37 < |\eta| < 1.52$. The Medium identification has an efficiency of 80% to 90%. The clusters are additionally required to pass the ‘FCHighPTCaloOnly’ isolation criteria [60].

Muons are reconstructed from signals in the MS matched with tracks in the ID. They are required to satisfy the ‘Medium’ identification criteria and the ‘FCLoose’ isolation criteria [61], and to have $p_T > 7$ GeV and $|\eta| < 2.5$. The Medium identification has an efficiency above 97%.

Since the objects used in the analysis are reconstructed from the same set of tracks and calorimetric energy clusters, some constituents can be associated with multiple objects. These overlaps between different objects are resolved with the procedure described in ref. [62].

4 Modelling

The data are modelled using Monte Carlo (MC) event samples corresponding to the dominant Drell-Yan process and the top-quark processes that contribute significantly to events containing one or more b -jets. The small diboson and Higgs boson components are also modelled using

MC. A final component consists of one or two hadronic jets misreconstructed as τ_{had} objects, and is evaluated using data-driven techniques.

4.1 Monte Carlo samples

The Drell-Yan production of lepton pairs is modelled using SHERPA 2.2.11 [63] events generated with matrix-element calculations at next-to-leading order (NLO) in QCD for up to two additional partons, and calculations at leading order (LO) for up to five additional partons using the COMIX [64] and OPENLOOPS [65–67] libraries. The calculations are matched to the SHERPA parton shower based on Catani-Seymour dipole factorisation [64, 68] using the MEPS@NLO prescription [69–72]. The NNPDF3.0NNLO parton distribution functions (PDFs) [73] are used. Uncertainties in the Drell-Yan predictions are estimated by comparing distributions to those from events generated with the POWHEG BOX v1 [74–77] generator at NLO accuracy in QCD and interfaced to PYTHIA 8.186 [78] for the modelling of the parton shower, hadronisation, and underlying event, with parameters set according to the AZNLO set of tuned parameters (tune) [79]. For these events, the CT10NLO PDF set [80] is used for the hard-scattering process, and the CTEQ6L1 PDF set [81] is used for the parton shower. The effect of QED final-state radiation was simulated with PHOTOS++ 3.52 [82, 83], and the EVTGEN 1.2.0 program [84] is used to decay bottom and charm hadrons.

The production of $t\bar{t}$ events is modelled using the POWHEG BOX v2 generator at NLO in QCD with the NNPDF3.0NLO PDF set and the h_{damp} parameter² set to $1.5 m_{\text{top}}$ [85]. The events are interfaced to PYTHIA 8.230 [86] to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune [87] and using the NNPDF2.3LO [88] set of PDFs. The decays of bottom and charm hadrons are performed by EVTGEN 1.6.0. Parton-shower uncertainties are estimated by replacing the PYTHIA parton shower with that of HERWIG 7.13 [89, 90] using the default set of tuned parameters and the MMHT2014 PDF set [91]. The uncertainty in the matching of the matrix element (ME) to the parton shower is estimated using events generated with the PYTHIA ‘POWHEG::pThard=1’ option, which changes the scale from the minimum p_{T} of all final-state particles in the POWHEG calculation to the p_{T} of the POWHEG emission.

Individual top quarks can be produced in association with a W boson, in the t -channel, or in the s -channel. Single-top processes are modelled using the POWHEG BOX v2 generator at NLO in QCD using the NNPDF3.0NLO PDF set, interfaced to PYTHIA 8.230 using the A14 tune and the NNPDF2.3LO PDF set. The four-flavour (five-flavour) scheme is used for t -channel (s -channel and associated) production. For associated production the diagram subtraction scheme [85, 92] is used to remove interference and overlap with $t\bar{t}$ production. The related uncertainty is estimated by comparing with an alternative sample generated using the diagram removal scheme [85, 92]. Uncertainties due to the parton shower model are evaluated using samples interfaced to HERWIG 7.04 with the default parameters and the MMHT14LO PDF set. Uncertainties in the matching of the parton shower to the ME

²The h_{damp} parameter is a resummation damping factor and one of the parameters that controls the matching of POWHEG matrix element to the parton shower and thus effectively regulates the high- p_{T} radiation against which the $t\bar{t}$ system recoils.

are evaluated using a sample generated with MADGRAPH5_AMC@NLO 2.6.2 [93] using the NNPDF2.3NLO PDF set.

Diboson production (VV) with fully leptonic and semileptonic final states are modelled with the SHERPA 2.2.11 generator using matrix elements calculated at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions. The loop-induced $gg \rightarrow VV$ processes are modelled using LO ME calculations for up to one additional parton emission. The ME calculations are matched to the SHERPA parton shower using the MEPS@NLO prescription. The virtual QCD corrections are provided by the OPENLOOPS library. The NNPDF3.0NNLO set of PDFs is used, along with the dedicated set of tuned parton-shower parameters developed by the SHERPA authors.

Higgs boson production ($H \rightarrow \tau\tau$) via gluon-gluon fusion is simulated at next-to-next-to-leading-order (NNLO) accuracy in QCD using POWHEG BOX v2 [74–76, 94, 95]. The PDF4LHC15NNLO PDF set [96] and the AZNLO tune of PYTHIA 8 are used. The Monte Carlo sample is normalized to the next-to-NNLO cross-section in QCD plus electroweak corrections at next-to-leading order [97–107]. The normalization accounts for the decay branching ratio calculated with HDECAY [108–110] and PROPHECY4F [111–113].

Potential off-shell leptoquark and Z' boson contributions to high-mass Drell-Yan production are modelled with MADGRAPH5_AMC@NLO 2.9.9 using LO-accurate matrix elements with up to two final-state partons. The samples are generated using the ‘vector_LQ_UFO’ model [114] and correspond separately to contributions from BSM interference with the SM amplitude and from BSM-only amplitudes. In the off-shell regime the kinematics of b -jets are similar between SM and BSM amplitudes, so the calculation consists of an SM amplitude at LO with up to two additional partons, reweighted to the predictions for several leptoquark and Z' boson parameters. The ME calculation employs the NNPDF2.3LO set of PDFs, and the events are interfaced to PYTHIA 8.306 [115] for the modelling of the parton shower, hadronisation, and underlying event. The A14 tune of PYTHIA is used with the NNPDF2.3LO PDF set. The overlap between ME and parton shower emissions is removed using the CKKW-L merging procedure. The decays of bottom and charm hadrons are performed by EVTGEN 1.2.0.

The MADGRAPH5_AMC@NLO calculation of Drell-Yan in association with b -jets is validated by comparing the ATLAS measurement of $Z + b$ -jet production [116] to the predictions of MADGRAPH5_AMC@NLO generated at the same order and with the same merging procedure as used for the signal sample. The MADGRAPH5_AMC@NLO predictions agree with the measurement to within its precision of 5%. The signal generation is further validated by comparing $\tau\tau b$ production using the leptoquark signal model to the same process using the SM reweighted to the signal model. The cross-sections agree to better than 10%. Uncertainties in the signal cross-sections from renormalization and factorization scale variations, and from PDF variations, are of this order or larger.

Effective dimension-6 interactions involving τ -leptons are modelled using MADGRAPH5_AMC@NLO 2.9.9 with ME calculations from the SMEFTSim 3.0 ‘topU3l’ model [117]. Events are generated by setting one of the Wilson coefficients to $1/\text{TeV}^2$ and reweighting to the others. In the fit to data the coefficients are rescaled as necessary to correspond to those of the ‘top’ model. Beyond the ME-level the samples are processed in the same way as for the leptoquark and Z' boson samples.

Process	Generator	Perturbative order (QCD)	PDF
Drell-Yan	SHERPA	NLO (≤ 2 partons), LO (3–5 partons)	NNPDF3.0NNLO
$t\bar{t}$, single top	POWHEG + PYTHIA 8	NLO	NNPDF3.0NLO
VV	SHERPA	NLO (≤ 1 parton), LO (2–3 partons)	NNPDF3.0NNLO
$H \rightarrow \tau\tau$	POWHEG + PYTHIA 8	NNLO	PDF4LHC15NNLO
Non-SM	MADGRAPH5_AMC@NLO + PYTHIA 8	LO	NNPDF2.3LO

Table 1. Monte Carlo samples used to model the SM and non-SM processes. Additional samples are used to estimate systematic uncertainties.

Table 1 summarizes the modelled processes and the event generators used in the analysis. For all samples, the effect of multiple interactions in the same and neighbouring bunch crossings is modelled by overlaying the simulated hard-scattering event with inelastic proton-proton (pp) events generated with PYTHIA 8.186 using the NNPDF2.3LO set of parton distribution functions and the A3 set of tuned parameters [118]. The ATLAS detector is modelled using a simulation [119] based on GEANT4 [120].

4.2 Misreconstructed τ_{had} background

Some τ_{had} candidates originate from hadronic jets, i.e. they are misreconstructed. Events with one jet misreconstructed as a τ_{had} object arise predominantly from $W(\rightarrow \tau\nu)$ +jets production, and events with two misreconstructed jets arise from QCD multijet production. Both backgrounds are estimated using a ‘fake-factor’ technique [46], where a sample enriched in misreconstructed jets is used to predict the contribution in the measurement sample.

The Tight τ_{had} objects used in this analysis include a requirement that the RNN score be larger than 0.8. Exclusive background-enriched regions are selected by requiring one or two τ_{had} objects to have $\text{RNN} < 0.8$. The extrapolation to the selection region is performed using a fake factor, defined as the ratio of misreconstructed jets satisfying $\text{RNN} > 0.8$ to those with $\text{RNN} < 0.8$. The value of the fake factor depends on the parton-level source of the jet, and is ≈ 3 times larger for quark-initiated jets than for gluon-initiated jets. The source of the jets in the background-enriched region must therefore be estimated in order to obtain an accurate fake factor for extrapolation.

An effective discriminant for a jet’s origin is its width, defined as the sum of the ΔR -weighted p_{T} of its constituents, divided by the total p_{T} [121]. The width of the τ_{had} object is calculated using its associated calorimeter clusters, and its distribution is obtained in quark-enriched $Z(\rightarrow \mu\mu)$ +jets events and in gluon-enriched multijet events [46]. Jets in the latter set of events are further divided into those arising from the hard scatter and those arising from pile-up, via the JVT algorithm. The fake factor is calculated in each sample. The fake factors are shown as a function of the p_{T} of the τ_{had} object in figure 1(a).

The normalization of each τ_{had} source in the background-enriched region is determined from fits to the width distribution as a function of p_{T} and η , for one or three associated

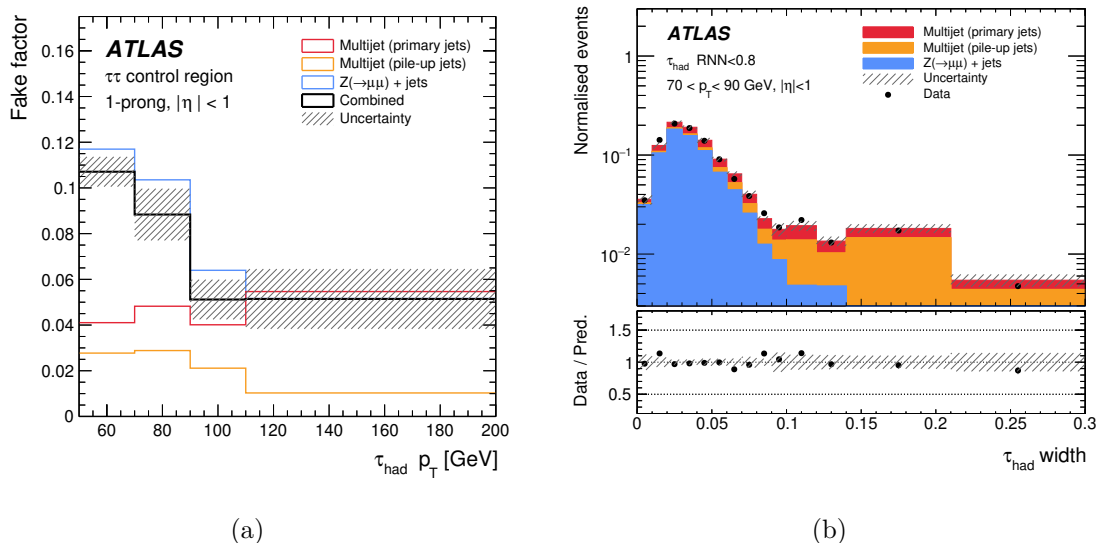


Figure 1. (a) The fake factor as a function of $\tau_{\text{had}} p_T$ for each category of events and τ_{had} objects with one associated charged track and $|\eta| < 1$. The overall fake factor used in the analysis (black hatched) is determined using the relative fractions of the categories obtained from the width fit. (b) The result of the width fit for τ_{had} objects with one associated charged track, p_T between 70 and 90 GeV, and $|\eta| < 1$. The ratio of data to prediction is shown in the bottom panel, along with the combined statistical uncertainty in the templates (hatched band). This fit is used to obtain the overall fake factor in the second bin of the left-hand plot.

charged tracks. Figure 1(b) shows the results of a fit to the τ_{had} object width in events with one τ_{had} object with $\text{RNN} < 0.8$ and one with $\text{RNN} > 0.8$, where the object with $\text{RNN} < 0.8$ has one associated charged track, p_T between 70 and 90 GeV, and $|\eta| < 1$. Each fit determines the relative amount of each jet source, and the extrapolation to the selection region is performed by applying the appropriate source-weighted fake factor to each event. The resulting yield correctly accounts for the W +jets misreconstruction background, but it double-counts the contribution from the multijet background. This overestimate is corrected by subtracting this contribution, determined using events containing two τ_{had} objects with $\text{RNN} < 0.8$ multiplied by the appropriate fake factors.

The uncertainty in the background estimate is dominated by statistical uncertainties in the template histograms used for the fit to the τ_{had} width, in the fit parameters, in the individual fake factors, and in the yield of τ_{had} objects with $\text{RNN} < 0.8$. The method is validated using events with two same-charge τ_{had} objects and events with one τ_{had} object and a same-charge muon or electron. The majority of these events contain a misreconstructed τ_{had} object. Events with an electron also contain a sizeable contribution from the Drell-Yan production of electron pairs, where an electron is misreconstructed as a τ_{had} ; this component is estimated using simulation rather than included in the misreconstructed τ_{had} background. Figure 2 shows that the predictions are consistent with the data over a large range of reconstructed invariant mass ($m_{\tau_{\text{had}}\tau_{\text{had}}}$ or $m_{\ell+\tau_{\text{had}}}$), given the approximately 10% uncertainty in the prediction.

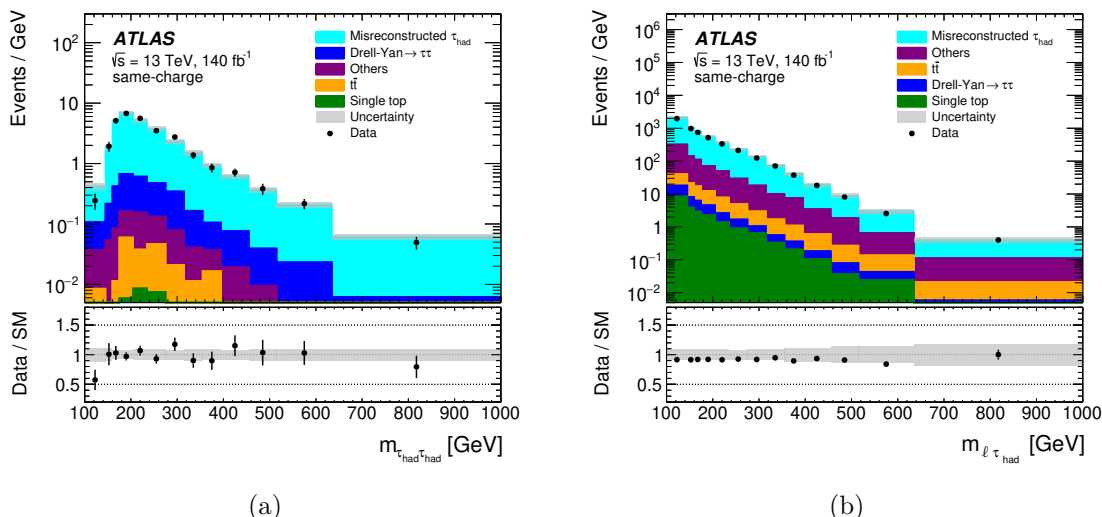


Figure 2. The distribution of the visible invariant mass of (a) two same-charge τ_{had} objects or (b) one τ_{had} object and an electron or muon with the same charge. The bottom panels show the ratio of data to the SM prediction, with the shaded band representing the total uncertainty in the prediction. The processes labelled ‘Others’ are the production of dibosons, Higgs bosons, and Drell-Yan pairs of electrons and muons. The events are used to validate the estimate of the misreconstructed τ_{had} background.

5 Measurement of the inclusive $\tau_{\text{had}}\tau_{\text{had}}$ cross-section

The measured differential cross-section is defined by kinematic selections of final-state particles such that they lie within a fiducial phase space which closely reflects the acceptance of the detector. This ensures minimal extrapolation from the observed detector-level data to the unfolded particle-level cross-sections, and minimal model dependence in the final particle-level measurement.

5.1 Definition of the measured final state

Particle-level τ_{had} candidates are built from the visible decay products of prompt, hadronically-decaying τ -leptons; the momentum sum of these visible decay products (the ‘visible momentum’) must yield $p_T > 20$ GeV and $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$). ‘Prompt’ here means that the lepton does not have a hadron ancestor beyond the initial-state protons.

Only events with exactly two fiducial τ_{had} objects, as defined above, contribute to the cross-section. The τ_{had} with the highest p_T is required to have $p_T > 90$ GeV, and the other is required to have $p_T > 60$ GeV. They are required to have opposite signs, and their visible components are used to build the particle-level $m_{\tau\tau}^{\text{vis}}$. As in refs. [122] and [123], fiducially accepted events need not originate from any particular production process, be that Drell-Yan, $t\bar{t}$, multi-boson, tW , or some other source. Any event that meets the particle-level fiducial requirements is treated as signal and will be included in the reported unfolded cross-sections.

5.2 Correction for detector effects

The detector-level distribution of the visible $\tau_{\text{had}}\tau_{\text{had}}$ invariant mass is shown in figure 3. The detector-level data are compared to the SM prediction consisting of the MC-estimated

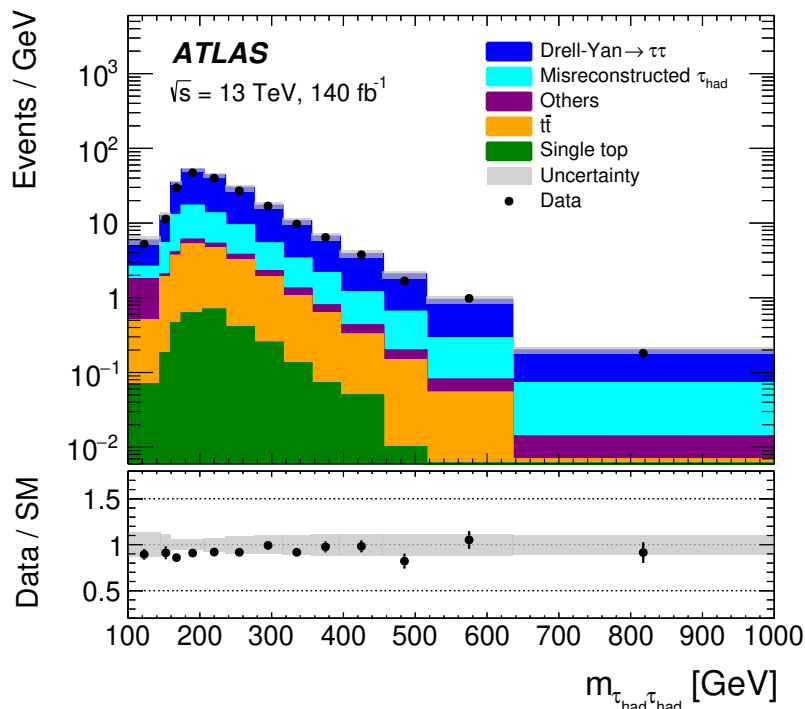


Figure 3. The $\tau_{\text{had}} \tau_{\text{had}}$ visible invariant mass in the region of the measurement, before background subtraction and correction for detector effects.

contributions from SM processes producing τ pairs, as well as the contribution from misidentified τ_{had} objects. The data are well modelled by the simulation.

Detector effects are unfolded using an iterative Bayesian method [124] to yield a detector-agnostic measurement of fiducial, differential cross-sections binned in $m_{\tau\tau}^{\text{vis}}$. The key ingredients to such an unfolding are the reconstruction efficiency, the backgrounds from misidentified τ_{had} objects, and the migrations between particle and detector level caused by the detector response, as encoded in the transfer, or migration, matrix. The method reweights the input distribution in a series of iterations based on the level of agreement between the data and the simulation, progressively removing the bias from the input distributon. Two iterations are used in this case, a number which was found to be the optimal compromise between the bias, which decreases with each iteration, and the statistical uncertainty, which increases.

Non-fiducial events are defined as those that do not pass the particle-level event selection: that is, they either fail the particle-level object selection (for example they do not contain two true τ -leptons) or the object kinematics fall out of the fiducial acceptance. Non-fiducial events constitute around 27% of the events in the bin around $m_{\tau\tau}^{\text{vis}} = 150$ GeV, falling to around 4% of the events at masses above 200 GeV. Contributions from this background are taken from MC predictions and accounted for as part of the unfolding procedure.

For the fiducial events which also pass the event selection criteria at the detector level, there will be migrations between mass bins due to the finite resolution of the detector. The transfer matrix describing these migrations using the off-diagonal matrix cells is evaluated using the nominal SHERPA samples, and is shown in figure 4. The efficiency is the diagonal

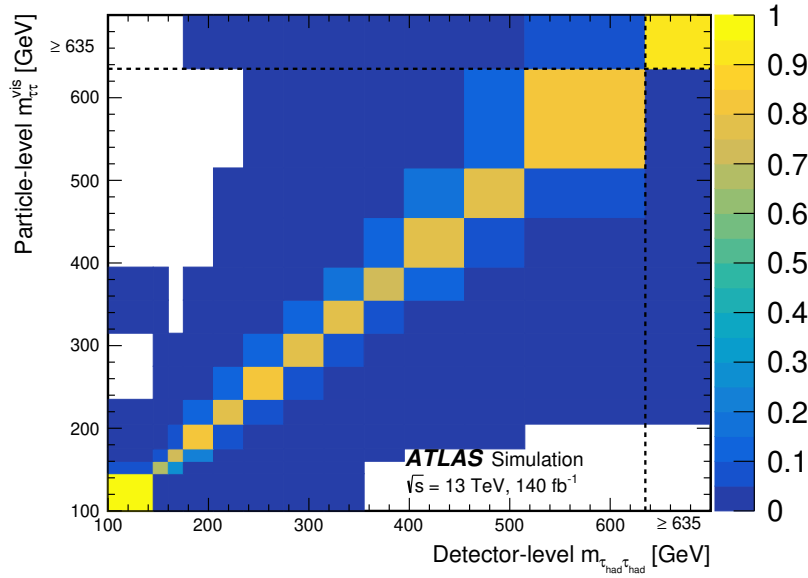


Figure 4. The nominal transfer matrix, showing the probability of an event from a fiducial $m_{\tau\tau}^{\text{vis}}$ bin to be reconstructed at detector-level in a given bin of $\tau_{\text{had}}\tau_{\text{had}}$ invariant mass.

component of the migration matrix, divided by the sum of the truth row for each bin and the number of events with a true $m_{\tau\tau}^{\text{vis}}$ in that bin but no reconstructed τ -lepton pair. It is around 15% for $m_{\tau\tau}^{\text{vis}} > 200$ GeV.

The purity in each bin is the fraction of fiducial events in a given detector-level bin which are in the same bin at particle-level. This is essentially the diagonal component of the migration matrix divided by the sum of the reconstruction level column for each bin. It is about 70% for masses of 150 GeV, and larger everywhere else.

The systematic uncertainties in the unfolded cross-section are evaluated by shifting the MC sample by the relevant uncertainty, re-evaluating the transfer matrix and redoing the unfolding. The total statistical uncertainty is evaluated similarly, by generating bootstraps from a Poisson distribution [125]. To assess any bias in the procedure, additional pseudodata sets were created by injecting simulated BSM events generated using the leptoquark model discussed in the following section, as well as by varying the SM subprocess composition of the sample (the most important being varying the contribution of top processes compared to Drell-Yan within their uncertainties) and by reweighting the visible τ_{had} p_T distribution of the nominal SM sample to data. In each case the (pseudo)data were then unfolded using the nominal response matrix derived from purely SM events. The biases were found to be small, and where significant are included in the modelling uncertainty.

The systematic uncertainty breakdown obtained for each subsample is shown in figure 5. It can be seen that the most important uncertainties are the modelling and τ -lepton identification uncertainties, especially near the low mass threshold, with the statistical uncertainty rising from around 8% at low $m_{\tau\tau}^{\text{vis}}$ to 15% at the highest values. The total uncertainty rises to close to 50% at low mass, principally due to the fact that in this region the τ -lepton candidates lie close to the p_T threshold.

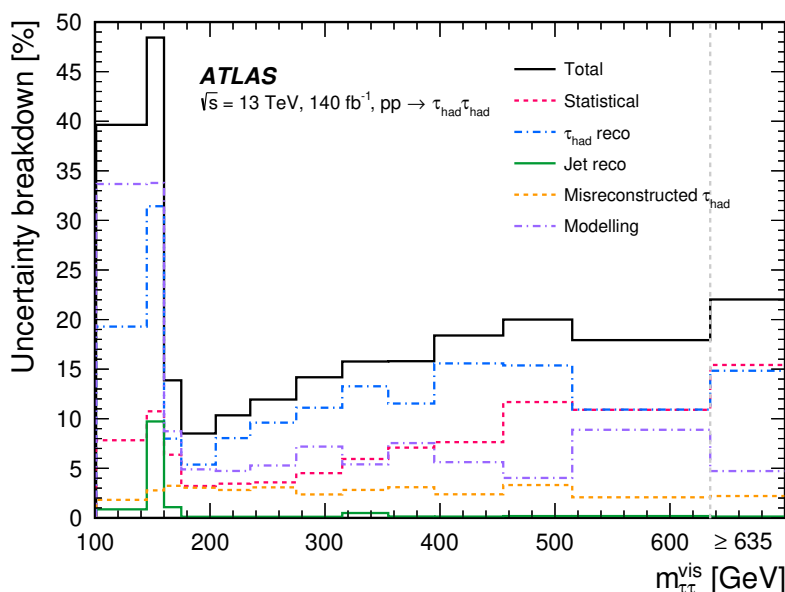


Figure 5. Uncertainty breakdown for the $m_{\tau\tau}^{\text{vis}}$ differential cross-section measurement.

5.3 Results

The measured cross-section is shown in figure 6. It peaks at $m_{\tau\tau}^{\text{vis}} \approx 200$ GeV, falling in magnitude below this value because only a small fraction of events at lower masses satisfy the transverse momentum cuts of 90 GeV and 60 GeV which form part of the definition of the fiducial cross-section. The measurement is compared to SM predictions from SHERPA 2.2.11 (MEPS@NLO) and POWHEG BOX +PYTHIA 8 (NLOPS), where all SM processes that contribute significantly to the cross-section are considered (principally top production and Drell-Yan). The uncertainty bars on the data contain all experimental uncertainties. The uncertainties in the SM predictions include the effect of QCD renormalization and factorization scale variations, and PDF uncertainties.

The theory predictions from both MEPS@NLO and NLOPS lie within the uncertainty bars of the unfolded data. At lower masses the predictions lie somewhat above the data, with the agreement improving for $m_{\tau\tau}^{\text{vis}} > 300$ GeV. The covariance matrix for the uncertainties is constructed, under the assumption that the theory and experimental uncertainties are normally distributed. Using this matrix, the p-value for the fit is 0.78. The results are made available in HEPData [126], with an accompanying Rivet routine [127].

6 Search for new non-resonant interactions

Generic non-resonant interactions can be described by an effective field theory (EFT). Of particular interest in the $\tau\bar{\tau}$ final state are preferential couplings to third-generation fermions. Such couplings would enhance the effect on the $\tau\bar{\tau}$ mass distribution in events with one or two b -jets, as the presence of b -jets suggests the primary interaction involves b -quarks. Since the background also depends on b -jet multiplicity, the analysis is separated into events with 0, 1, or

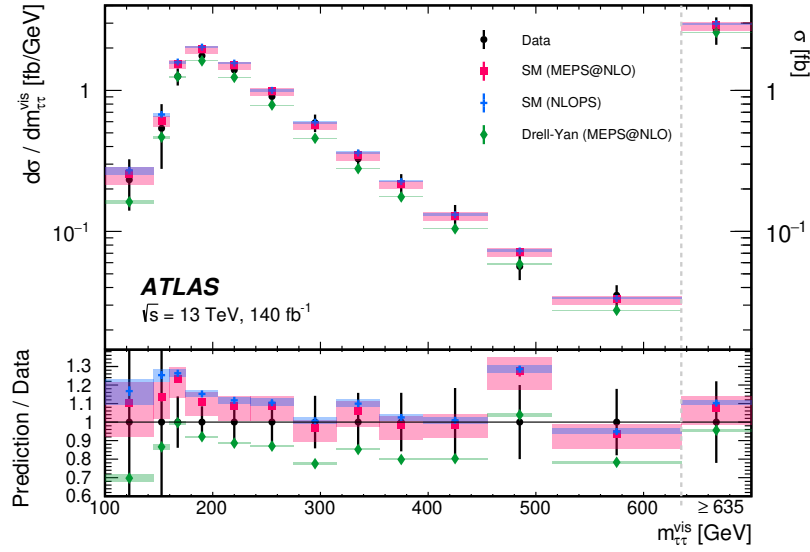


Figure 6. Unfolded fiducial cross-section, differential in $m_{\tau\tau}^{\text{vis}}$, compared with SM predictions from MEPS@NLO (SHERPA 2.2.11) and NLOPS (POWHEG BOX +PYTHIA 8), where all SM processes that contribute significantly to the cross-section are considered. The curve labelled ‘Drell-Yan (MEPS@NLO)’ corresponds to the SHERPA 2.2.11 generated Drell-Yan process only, shown with only MC statistical uncertainties, to indicate the expected contribution from this process. The rightmost bin is an overflow bin, integrating the cross-section above 635 GeV, as indicated on the right-hand axis label.

at least 2 b -jets. A profile likelihood fit to the data is performed for general $\tau\tau qq$ and $Z(/ \gamma)\tau\tau$ EFT couplings, and for leptoquarks and Z' bosons coupling preferentially to b -quarks.

6.1 SM effective field theory

The general Lagrangian of an EFT respecting the Standard Model gauge symmetries can be expressed as:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \dots, \quad (6.1)$$

where the operators $\mathcal{O}^{(6)}$ have mass-dimension six, the suppression mass scale is Λ , c_i are dimensionless coupling coefficients, and mass-dimension-five operators are neglected since they are lepton-number-violating and strongly constrained by neutrino measurements [128]. The EFT assumes that the new-physics scale is above the mass scale directly accessible to the measurement.

Assuming no flavour symmetries and no baryon-number-violating operators, there are 2499 independent operators in the Standard Model effective field theory (SMEFT). To reduce the parameter space, the ‘top’ model assumes the first two quark generations are flavour-symmetric. The coupling coefficients of this model have been constrained by prior ATLAS global fits to measured observables [129]. The operators relevant to $pp \rightarrow \tau\bar{\tau}$ production are four-fermion operators, operators with $V\tau\tau$ interactions, and the four-lepton operator that affects muon decay, since the muon lifetime is used to set the weak coupling G_F .

The probed ‘top’ operators are shown in table 2. Four-fermion operators involving b -quarks are not considered since the leptoquark and Z' -boson models map onto these operators. Operators connecting a left-handed fermion to its right-handed counterpart lead to cross-sections too small to be probed by this analysis. The coefficient defined as $c_{\tau\gamma}$ is a linear combination of ‘top’ operators that contributes to the anomalous magnetic moment of the τ -lepton, a_τ , and to the electric dipole moment d_τ if $c_{\tau\gamma}$ is complex [130–133]:

$$\delta a_\tau = \frac{2\sqrt{2}m_\tau v}{e} \frac{\text{Re}[c_{\tau\gamma}]}{\Lambda^2}, \quad \delta d_\tau = \sqrt{2}v \frac{\text{Im}[c_{\tau\gamma}]}{\Lambda^2},$$

where v is the Higgs field vacuum expectation value, e is the electron electric charge, m_τ is the τ -lepton mass, and δ indicates deviations from the Standard Model anomalous moments. The corresponding coefficient for $Z\tau\tau$ interactions is defined as $c_{\tau Z}$. While the coefficients are taken to be real in the event generation, constraints can nonetheless be inferred for δd_τ (see section 6.5).

The scale Λ is assumed to be sufficiently high that the interference between the SMEFT and SM diagrams dominates. Fits performed to individual coupling coefficients using this interference as the signal are referred to as ‘linear’ fits since they depend linearly on the coupling coefficients. As a check of the validity of the constraints, an additional fit is performed including both the interference and the pure SMEFT contribution for each coefficient assuming $\Lambda = 1$ TeV. These fits are referred to as ‘linear plus quadratic’ fits. In the case of the operators contributing to $c_{\tau\gamma}$ and $c_{\tau Z}$, the interference is suppressed by m_τ/Λ and the dominant contribution is from the pure-SMEFT quadratic term.

6.2 Leptoquark models

The Lagrangian terms relevant for non-resonant $\tau\bar{\tau}$ production from t-channel vector leptoquark (U) exchange are [114]:

$$\Delta\mathcal{L} = U^\mu (\beta_L^{i3} \bar{q}_L^i \gamma_\mu \ell_L^3 + \beta_R^{i3} \bar{q}_R^i \gamma_\mu \tau_R) / \sqrt{2} + \text{h.c.}, \quad (6.2)$$

where β_L^{i3} and β_R^{i3} are the couplings to the left-handed and right-handed fermion states, respectively, q_L^i is the left-handed quark doublet of generation i , and ℓ_L^3 is the third-generation left-handed lepton doublet. For $i = 3$, the dominant non-resonant diagrams consist of either an initial $b\bar{b}$ pair or an initial state of a gluon and a b or $\bar{b}$, where the gluon splits into a $b\bar{b}$ pair (figure 7). A leptoquark is exchanged in the t-channel to produce a pair of τ -leptons.

The signal diagrams destructively interfere with the dominant SM process of Drell-Yan production. For values of $\beta_{L,R}^{i3}$ larger than one, there can be large cancellations between the interference and the pure-BSM contribution. However, the two contributions have different $\tau\tau$ mass dependence, which can be exploited to improve sensitivity. The maximum sensitivity to the process comes from events with one associated b -jet. For such events within a range of visible mass of 100–250 GeV, interference contributes -34 ± 4 events while pure-BSM contributes 19 ± 3 events for a leptoquark mass of 2 TeV and $(\beta_L^{33})^2 = 10$; in the mass range 400–1000 GeV the contributions are -11 ± 2 and 39 ± 12 events, respectively, where the uncertainties are statistical.

The signal samples are generated with MADGRAPH5_AMC@NLO, as described in section 4. Events are generated using the SM process and subsequently reweighted to the

Coupling coefficient	Operator
$c_{lq}^{(3)}$	$(\bar{l}\sigma^i\gamma^\mu l)(\bar{q}\sigma^i\gamma^\mu q)$
$c_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)(\bar{q}\gamma^\mu q)$
c_{lu}	$(\bar{l}\gamma^\mu l)(\bar{u}\gamma^\mu u)$
c_{ld}	$(\bar{l}\gamma^\mu l)(\bar{d}\gamma^\mu d)$
$c_{q\tau}$	$(\bar{\tau}\gamma^\mu\tau)(\bar{q}\gamma^\mu q)$
$c_{\tau u}$	$(\bar{\tau}\gamma^\mu\tau)(\bar{u}\gamma^\mu u)$
$c_{\tau d}$	$(\bar{\tau}\gamma^\mu\tau)(\bar{d}\gamma^\mu d)$
c_{ll}	$(\bar{\mu}\gamma^\mu\mu)(\bar{e}\gamma^\mu e)$
$c_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^i H)(\bar{l}\sigma^i\gamma^\mu l)$
$c_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$
$c_{H\tau}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\tau}\gamma^\mu\tau)$
$c_{\tau W}$	$(\bar{l}\sigma^{\mu\nu}\tau)\sigma^i H W_{\mu\nu}^i$
$c_{\tau B}$	$(\bar{l}\sigma^{\mu\nu}\tau)HB_{\mu\nu}$
$c_{\tau Z}$	$(\bar{l}\sigma^{\mu\nu}\tau)\sigma^i H(c_W\sigma^i W_{\mu\nu}^i + s_W B_{\mu\nu})$
$c_{\tau\gamma}$	$(\bar{l}\sigma^{\mu\nu}\tau)\sigma^i H(-s_W\sigma^i W_{\mu\nu}^i + c_W B_{\mu\nu})$

Table 2. Coupling coefficients c_i and corresponding SMEFT operators $\mathcal{O}_i^{(6)}$ used in this analysis. The operator and coefficient notation follows the convention of the SMEFTSim 3.0 ‘top’ model, with e replaced by τ to explicitly indicate the probed lepton flavour. Right-handed states are labelled by particle type, with u referring to an up or charm quark and d referring to a down or strange quark. Left-handed states are labelled q for the quark doublet of either of the first two generations and l , μ , or e for the τ -lepton, muon, or electron doublet. The cosine and sine of the Weinberg angle are denoted c_W and s_W , respectively. The coupling coefficients are assumed to be real, and any necessary Hermitian conjugates are implied.

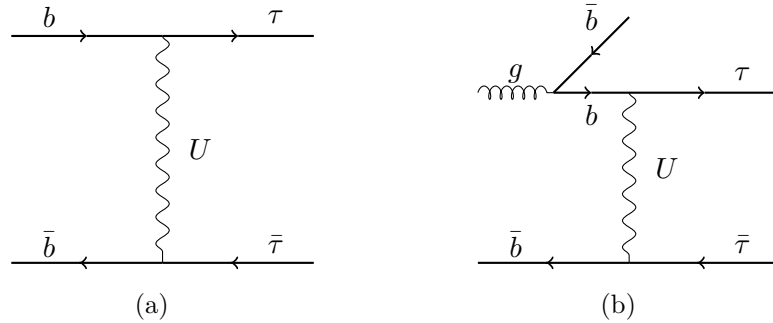


Figure 7. The leading non-resonant diagrams for an initial state of (a) $b\bar{b}$ or (b) $g\bar{b}$ and a final state of (a) $\tau\bar{\tau}$ or (b) $\tau\bar{\tau}\bar{b}$.

signal process for a variety of coupling and leptoquark-mass (m_U) values. Other values are obtained by interpolating according to the expected non-resonant scaling, $\sigma \propto (\beta_{L,R}^{i3})^2/m_U^2$ for interference and $\sigma \propto (\beta_{L,R}^{i3})^4/m_U^4$ for the pure-BSM contribution. Weights are included for the scenarios preferred by the B -hadron anomalies, $\beta_R^{33} = -\beta_L^{33}$ and $\beta_L^{33} \neq 0$, with other couplings equal to zero. Additional weights correspond to scenarios of pure right-handed couplings, $\beta_R^{33} \neq 0$, and left-handed couplings between second-generation quarks and third-generation leptons, $\beta_L^{23} \neq 0$.

Scalar leptoquarks are also probed according to the Lagrangian [134]:

$$\Delta\mathcal{L} = \lambda \bar{b}_R^C \tilde{S}_1 \tau_R + \text{h.c.}, \quad (6.3)$$

where C stands for charge conjugation and $\tilde{S}_1$ represents the leptoquark field. Signal samples are generated in the same manner as for vector leptoquarks, i.e. reweighting the SM process to that of scalar leptoquark exchange for a variety of mass values.

6.3 Z' boson model

The Lagrangian terms relevant for $\tau\bar{\tau}$ production from s-channel Z' boson exchange via $b\bar{b}$ annihilation are [114]:

$$\Delta\mathcal{L} = Z'^\mu (\zeta_q \bar{q}_L^3 \gamma_\mu q_L^3 + \zeta_u \bar{t}_R \gamma_\mu t_R + \zeta_d \bar{b}_R \gamma_\mu b_R - 3\zeta_\ell \bar{\ell}_L^3 \gamma_\mu \ell_L^3 - 3\zeta_\tau \bar{\tau}_R \gamma_\mu \tau_R) / (2\sqrt{6}), \quad (6.4)$$

where ζ_q (ζ_ℓ) and ζ_d (ζ_τ) are the couplings to third-generation left-handed and right-handed quark (lepton) states, respectively. The interference between the Z' boson diagram and SM $\tau\bar{\tau}$ production is constructive. The signal is modelled using the same MADGRAPH5_AMC@NLO samples as for leptoquark production. Weights are included for the benchmark cases where the Z' boson couples universally to left-handed fermions ($\zeta_q = \zeta_\ell \neq 0$) or to right-handed fermions ($\zeta_d = \zeta_\tau \neq 0$). Non-resonant production is ensured by reweighting to a Z' boson mass of 3 TeV and extrapolating to other mass points by approximating the propagator as the inverse square of the mass.

6.4 Fit frameworks

The various models are fit either to the observed data yields using a profile likelihood fit, or to the particle-level differential cross-section (figure 6) using a χ^2 minimization.

The profile likelihood fit is performed using the yields in three bins of b -jet multiplicity (0, 1, ≥ 2) and three bins of invariant mass of the $\tau_{\text{had}}\tau_{\text{had}}$ system (100–250, 250–400, and 400–1000 GeV). The bins are chosen to give the optimal sensitivity given the Monte Carlo statistical uncertainty of the signal sample. The parameter of interest is the square of the coupling tested in the model. Systematic uncertainties are included as nuisance parameters with Gaussian constraint terms in the likelihood function. The normalizations of the Drell-Yan and $t\bar{t}$ processes are freely floated in the fit, and are largely constrained by events with b -jet multiplicities of 0 and ≥ 2 , respectively.

Systematic uncertainties are fully correlated across the bins, with two exceptions. The generator modelling uncertainty in the Drell-Yan process is uncorrelated across b -jet multiplicity since the underlying source of uncertainty is expected to differ for each multiplicity

value. The misreconstructed τ_{had} background uncertainty is also uncorrelated across b -jet multiplicity since separate data sets are used in the extrapolation from low values to high values of the RNN discriminant in the background estimation.

The likelihood fit uses the `pyhf` [135] framework, which finds the shape of the likelihood function around the maximum. The `cabinetry` [136] toolkit is used to set up the fit and provide information on nuisance parameter impacts, pulls, and correlations. Exclusion limits are determined using a modified CLs technique [137, 138] with the profile-likelihood ratio as the test statistic, using the asymptotic approximation [139]. The fit model is constructed such that the parameter of interest scales linearly with the interference term and quadratically with the pure-BSM term.

The χ^2 fit is only performed for the SMEFT operator coefficients, which affect inclusive Drell-Yan production. The χ^2 is evaluated as described in section 5.3, with the addition of a signal term depending upon the SMEFT coupling and the inclusion of the corresponding signal uncertainties in the covariance matrix. The best-fit coupling is evaluated, and the likelihood ratio with respect to the likelihood at this value is used to evaluate a confidence level (CL) as a function of coupling. The general procedure is as described in detail in ref. [140]³.

6.5 Results

Figure 8 compares the $m_{\tau_{\text{had}}\tau_{\text{had}}}$ data distribution to the result of the SM-only fit and its sum with the $m_{\text{LQ}} = 2.5$ TeV leptoquark signal model with a coupling value of $\beta_L^{33}/\sqrt{2} = 2.5$ that is excluded by this measurement at the 95% CL. The difference between the SM and the data is less than one standard deviation in each bin of b -jet multiplicity. The fit gives overall multiplicative normalization factors of 0.88 ± 0.07 and 0.80 ± 0.10 for the Drell-Yan and $t\bar{t}$ processes, respectively. The leading uncertainties are the Drell-Yan modelling uncertainties in events with one b -jet, and the $t\bar{t}$ normalization and modelling uncertainties. These are followed by the MC statistical uncertainties in the bin with the highest $m_{\tau_{\text{had}}\tau_{\text{had}}}$ in $1b$ events.

The results of the likelihood fits for individual SMEFT coefficients are given in table 3; fits to the interference-only signal (‘linear’), as well as fits using both the interference and BSM terms (‘linear + quad.’), are shown. The interference term dominates the sensitivity to all coefficients except $c_{\tau B}$, $c_{\tau W}$, $c_{\tau Z}$, and $c_{\tau\gamma}$, for which this term is suppressed and the BSM term dominates. The best-fit value and 68% confidence interval are given for each coefficient at a scale of 1 TeV. In the linear case the coefficient values scale as $c(\Lambda) = c\Lambda^2/\text{TeV}^2$, so four-fermion interactions constrain scales up to about 5 TeV for unit coefficients. Constraints on effective $Z(/ \gamma)\tau\tau$ interactions are weaker, constraining the scale to more than 1 TeV for unit coefficients. These uncertainties and constraints are illustrated in figure 9. Results of the χ^2 fit to the particle-level differential cross-section are consistent with the detector-level fits and in general exhibit better constraining power than the detector-level fits for couplings that do not enhance b -production, due to the finer binning in $m_{\tau\tau}^{\text{vis}}$.

As discussed in section 6.1, $c_{\tau\gamma}$ affects the τ -lepton anomalous magnetic moment. Previous LHC constraints on a_τ [143–145] can be interpreted as constraints on $c_{\tau\gamma}$ using the EFT assumption that no new physics appears at a low mass scale. Figure 10 compares the results

³In the previous versions of CONTUR [140, 141], no signal fit was performed. The current version, Contur 3.1, uses SPEY [142] to obtain the best-fit signal.

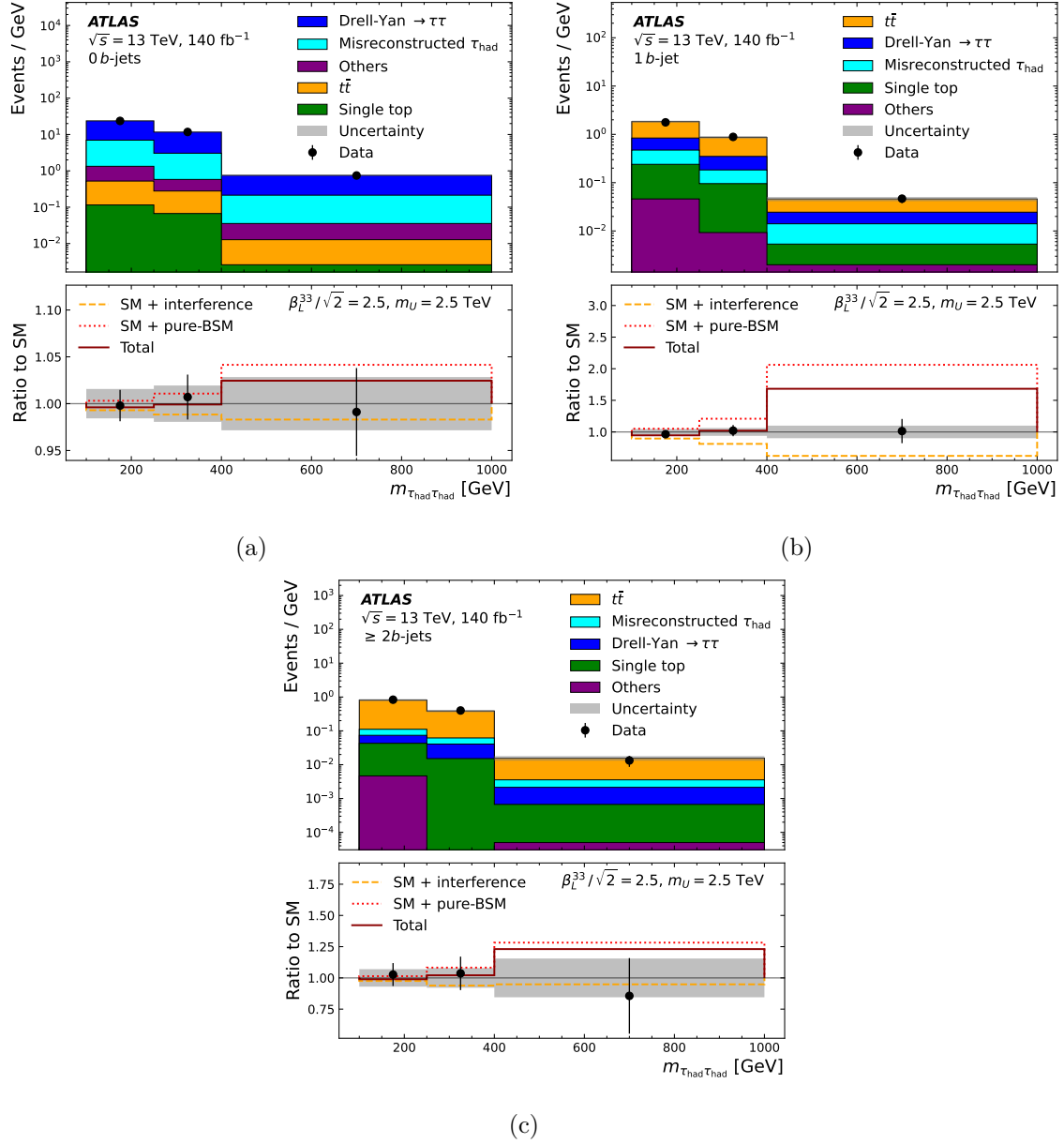


Figure 8. The background-only post-fit $\tau_{\text{had}}\tau_{\text{had}}$ visible invariant mass in events with (a) zero b -jets, (b) one b -jet, or (c) at least two b -jets. Shown are the data and the individual SM backgrounds, along with the ratio of the data to the SM. Also shown are the ratios of the sum of the SM prediction and either the interference, pure-BSM, or total signal to the SM prediction, for the case $\beta_L^{33}/\sqrt{2} = 2.5$ and a vector leptoquark mass of 2.5 TeV. The grey band shows the relative post-fit uncertainty on the SM prediction.

Coefficient	fit result (linear)	fit result (linear + quad.)
$c_{lq}^{(3)}$	$-0.002^{+0.018}_{-0.016}$	$-0.002^{+0.018}_{-0.016}$
$c_{lq}^{(1)}$	$0.01^{+0.06}_{-0.07}$	$0.01^{+0.18}_{-0.05}$
c_{lu}	$-0.05^{+0.15}_{-0.20}$	$-0.05^{+0.15}_{-0.20}$
c_{ld}	$-0.02^{+0.21}_{-0.21}$	$-0.02^{+0.21}_{-0.21}$
$c_{q\tau}$	$0.01^{+0.07}_{-0.08}$	$0.01^{+0.07}_{-0.16}$
$c_{\tau u}$	$0.01^{+0.04}_{-0.04}$	$0.01^{+0.04}_{-0.04}$
$c_{\tau d}$	$0.07^{+0.32}_{-0.25}$	$0.07^{+0.32}_{-0.25}$
$c_l^{(1)}$	$-1.1^{+1.1}_{-1.1}$	$-1.0^{+1.1}_{-1.1}$
$c_{Hl}^{(3)}$	$0.7^{+0.8}_{-0.8}$	$0.7^{+0.8}_{-0.8}$
$c_{Hl}^{(1)}$	$-1.7^{+1.6}_{-1.6}$	$-1.5^{+1.6}_{-1.6}$
$c_{H\tau}$	6^{+6}_{-6}	$0.7^{+2.1}_{-1.9}$
$c_{\tau W}$	15^{+15}_{-15}	$0.0^{+0.4}_{-0.5}$
$c_{\tau B}$	-30^{+31}_{-30}	$-0.2^{+1.8}_{-1.5}$
$c_{\tau Z}$	20^{+19}_{-20}	$0.0^{+0.4}_{-0.5}$
$c_{\tau\gamma}$	-17^{+17}_{-16}	$-0.1^{+1.0}_{-0.8}$

Table 3. Central values and 68% confidence intervals from the individual coupling coefficient fits when using the contribution linear in the coupling or using the linear and quadratic contributions. In the likelihood fits the scale is set to $\Lambda = 1$ TeV so the values from the linear fit have the dependence $c(\Lambda) = c\Lambda^2/\text{TeV}^2$.

of these measurements to that obtained from a χ^2 fit to the particle-level differential cross-section for $\tau\bar{\tau}$ production. The confidence interval from this measurement is about a factor of seven smaller than the ATLAS measurement in ultra-peripheral lead-lead collisions [143], and competitive with the CMS analysis of $\gamma\gamma \rightarrow \tau\bar{\tau}$ events in pp collisions [144].

The $c_{\tau\gamma}$ value of $-0.40^{+0.63}_{-0.24}$ from the χ^2 fit can be translated into an a_τ of $-0.5^{+2.6}_{-0.9} \times 10^{-3}$ with a 95% confidence interval of $[-2.4, 4.7] \times 10^{-3}$ using the relation in section 6.1 and adding the SM value $a_\tau = 1.178 \times 10^{-3}$; however, since a_τ is defined for on-shell photons ($q^2 = 0$) and this analysis relies on off-shell photon exchange, the interpretation should formally be restricted to the EFT parameter $c_{\tau\gamma}$. Nonetheless, one can apply the EFT assumption of no new physics at a low scale and further infer d_τ from a χ^2 fit for $c_{\tau\gamma}$ using the pure-SMEFT contribution of the corresponding operator. This contribution has the same dependence on the real and imaginary components of $c_{\tau\gamma}$ when it is complex, and there is negligible interference between the SM and $\text{Im}[c_{\tau\gamma}]$ -dependent matrix elements. The resulting fit value and 95% confidence interval are $0.9^{+0.6}_{-1.4} \times 10^{-17} e\text{ cm}$ and $[-2.0, 2.0] \times 10^{-17} e\text{ cm}$, respectively.

No evidence of a signal is observed and limits are set on leptoquark and Z' -boson couplings as functions of their masses. For the leptoquark coupling scenarios preferred by the B -hadron anomalies the limits exclude a small portion of the preferred coupling-mass plane (figure 11). Constraints are also set on the vector leptoquark couplings β_R^{33} and β_L^{23} ,

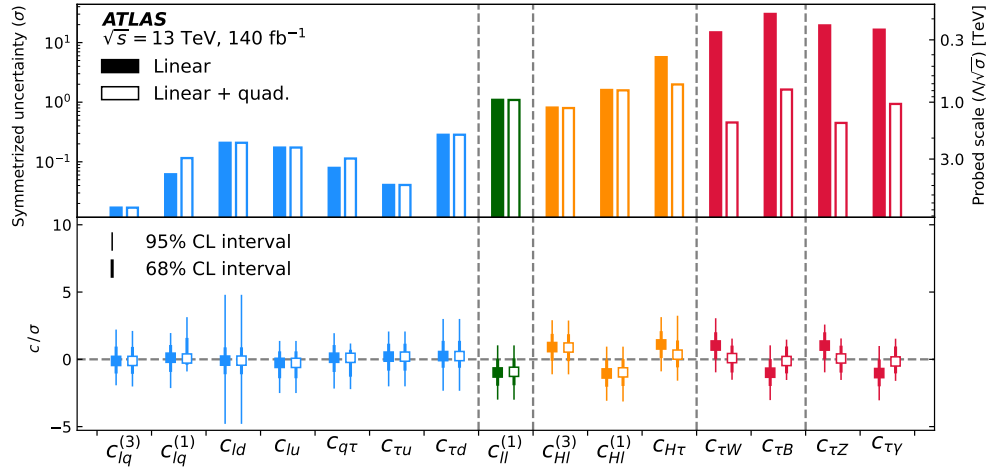


Figure 9. The results of likelihood fits for individual coupling coefficients using only the first-order expansion of the coupling (‘linear’) or the first-order and partial second-order contributions to the cross-section (‘linear + quad.’). The upper panel illustrates the symmetrized 1σ uncertainty in each coupling coefficient at a scale of $\Lambda = 1$ TeV (left y -axis) and the scale probed for a unit coefficient for the linear results (right y -axis). The lower panel shows the best-fit coefficient and the 68% and 95% confidence intervals relative to the symmetrized 1σ uncertainty.

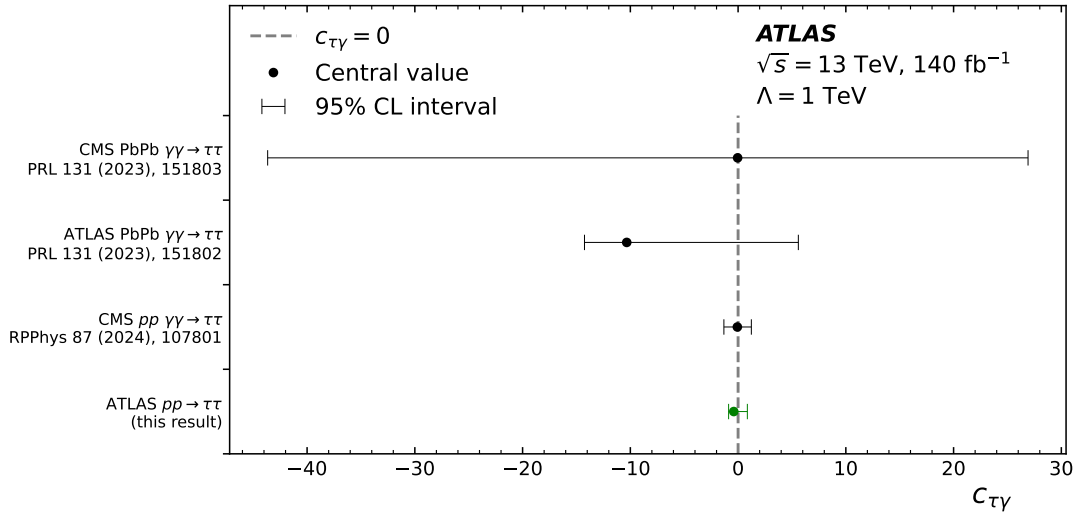


Figure 10. Comparison of central values and confidence intervals on $c_{\tau\gamma}$ from this measurement and measurements probing the τ -lepton anomalous magnetic moment [143–145].

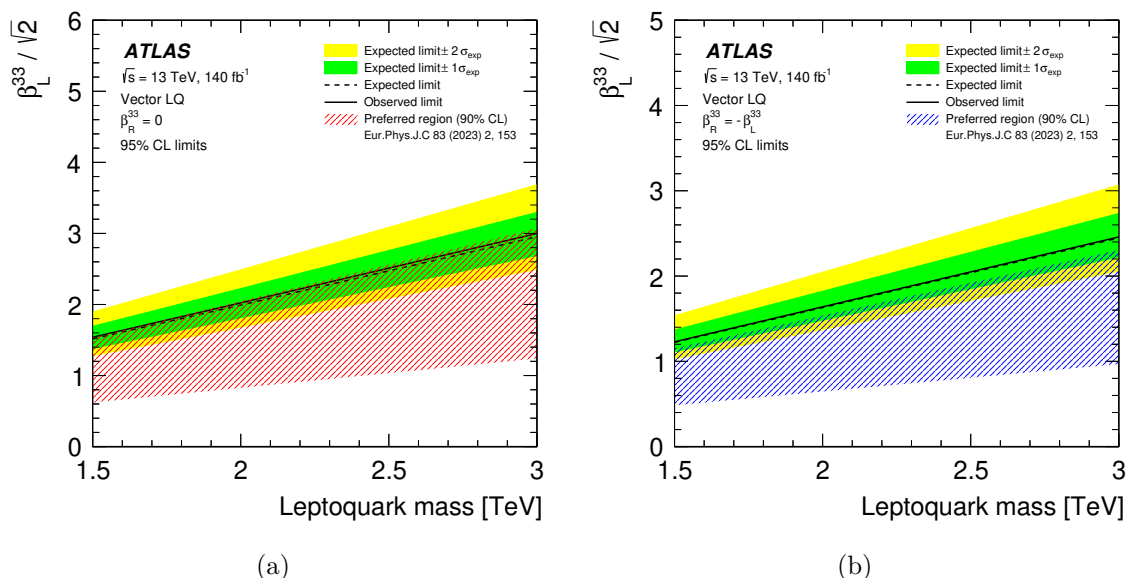


Figure 11. Coupling limits as a function of mass of a vector leptoquark coupling to a τ -lepton and a b quark. Shown are the observed (solid line) and expected limits (dashed line), along with the expected 68% (inner green band) and 95% (outer yellow band) confidence intervals, and the region preferred by measurements of B -hadron decays (shaded). Leptoquarks (a) coupling exclusively to left-handed fermions and (b) coupling to left-handed and right-handed fermions with equal magnitude and opposite sign are shown.

on the scalar leptoquark coupling λ , and on the Z' -boson coupling combinations $\sqrt{\zeta_q \zeta_\ell}$ and $\sqrt{\zeta_b \zeta_\tau}$, all shown in figure 12. The limits improve on previous constraints from ATLAS [37], and on those from CMS [38]. The CMS search for leptoquarks observed a local excess of 2.8 standard deviations that is most prominent for the non-resonant signal. In events without a b -jet CMS obtains a local significance between 3.4 and 3.7 standard deviations for the scalar and vector leptoquark models, using a benchmark leptoquark mass of 2 TeV and coupling equal to 2.5. This analysis excludes these benchmark parameter values for scalar and vector leptoquark models.

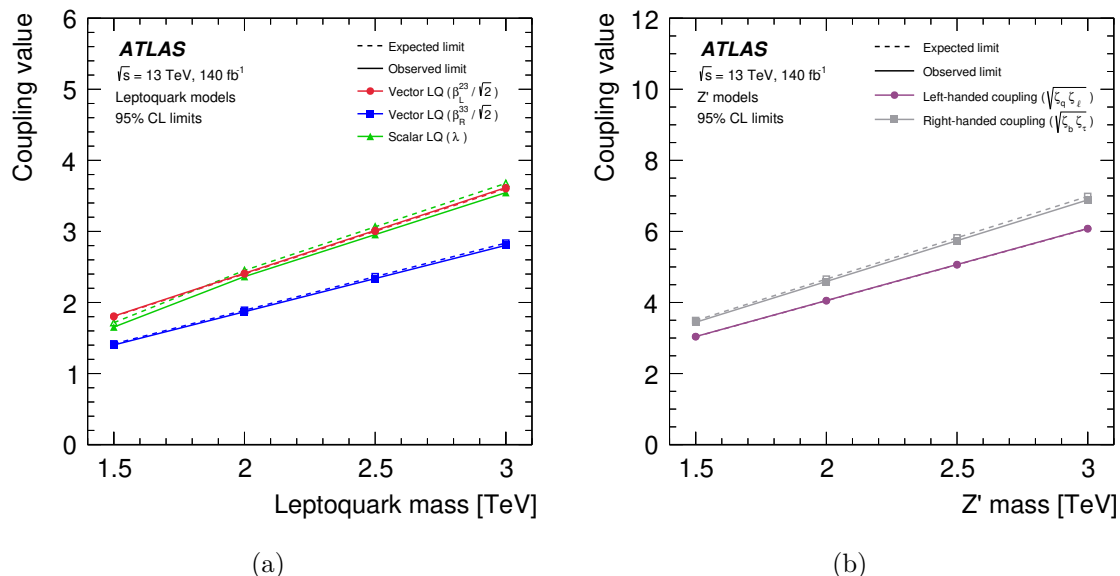


Figure 12. (a) Coupling limits as a function of mass of a vector (red and blue) or scalar (green) leptoquark coupling to a τ -lepton and a b quark. Here the vector leptoquark couples to right-handed fermions (blue) or to left-handed τ -leptons and second generation quarks (red). (b) The coupling limit as a function of mass for the non-resonant production of a Z' boson coupling to left-handed (dark line) or right-handed (light line) fermions.

7 Conclusion

The first unfolded differential measurement of inclusive $\tau\bar{\tau}$ production has been performed at the LHC, using 140 fb $^{-1}$ of proton-proton collision data recorded with the ATLAS detector. The measurement is consistent with the predictions of the Standard Model. In addition, the data have been fit directly for a variety of new non-resonant interactions. Interactions involving quarks of the first two generations are constrained using the SM effective field theory with a symmetry assumed between these generations. Interactions between a $\tau\bar{\tau}$ pair and a Z boson or photon are also constrained. Two models with enhanced couplings to third-generation fermions are constrained: those with a vector or scalar leptoquark, and those with a Z' boson.

Of particular interest are vector leptoquarks coupling to third-generation fermions with left-handed couplings or a left-minus-right-handed combination. Such couplings are preferred by B -hadron measurements that show tension with SM predictions. Sensitivity to these couplings is enhanced by separating the data by b -jet multiplicity, since the most sensitive final state contains one additional b -jet. The combination of interference and leptoquark-only couplings are included for the first time in this final state. The resulting constraints remove a small portion of the region preferred by the B -hadron measurements.

Acknowledgments

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [146].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMFTR, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

In addition, individual members wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN DOCT); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC — 12175119, NSFC 12275265); Czech Republic: Czech Science Foundation (GACR — 24-11373S), Ministry of Education Youth and Sports (ERC-CZ-LL2327, FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC — 101002463); European Union: European Research Council (BARD No. 101116429, ERC — 948254, ERC 101089007), European Regional Development Fund (SMASH COFUND 101081355, SLO ERDF), Horizon 2020 Framework Programme (MUCCA — CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Horizon 2020 (EuroHPC — EHPC-DEV-2024D11-051), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-21-CE31-0022, ANR-22-EDIR-0002); Germany: Baden-Württemberg

Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG — 469666862, DFG — CR 312/5-2); China: Research Grants Council (GRF); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell’Università e della Ricerca (NextGenEU I53D23000820006 M4C2.1.1); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245, JSPS KAKENHI JP24K23939); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920, UMO-2024/53/N/ST2/00869); Portugal: Foundation for Science and Technology (FCT); Spain: Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2021-03651, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR 2024-05451), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2022.0358, KAW 2023.0366); Switzerland: Swiss National Science Foundation (SNSF — PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

Data Availability Statement. This article has no associated data or the data will not be deposited.

Code Availability Statement. This article has no associated code or the code will not be deposited.

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R. Tafirout ^{162a}, Y. Takubo ⁸⁴, M. Talby ¹⁰⁴, A.A. Talyshev ³⁸, K.C. Tam ^{64b},
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M. Tomoto ^{84,113}, L. Tompkins ^{149,o}, E. Torrence ¹²⁶, H. Torres ⁹¹, E. Torró Pastor ¹⁶⁹,
M. Toscani ³¹, C. Toscizi ⁴⁰, M. Tost ¹¹, D.R. Tovey ¹⁴⁵, T. Trefzger ¹⁷², P.M. Tricarico ¹³,
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P.V. Tsiareshka ³⁹, S. Tsigaridas ^{162a}, A. Tsirigotis ^{158,v}, V. Tsiskaridze ¹⁶¹,
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J.C. Vermeulen ¹¹⁷, C. Vernieri ¹⁴⁹, M. Vessella ¹⁶⁵, M.C. Vetterli ^{148,ai}, A. Vgenopoulos ¹⁰²,

N. Viaux Maira [140g](#), T. Vickey [145](#), O.E. Vickey Boeriu [145](#), G.H.A. Viehhauser [129](#), L. Vigani [63b](#), M. Vigl [112](#), M. Villa [24b,24a](#), M. Villaplana Perez [169](#), E.M. Villhauer⁴⁰, E. Vilucchi [53](#), M. Vincent [169](#), M.G. Vinciter [35](#), A. Visibile¹¹⁷, C. Vittori [37](#), I. Vivarelli [24b,24a](#), E. Voevodina [112](#), F. Vogel [111](#), J.C. Voigt [50](#), P. Vokac [135](#), Yu. Volkotrub [86b](#), E. Von Toerne [25](#), B. Vormwald [37](#), K. Vorobev [51](#), M. Vos [169](#), K. Voss [147](#), M. Vozak [37](#), L. Vozdecky [123](#), N. Vranjes [16](#), M. Vranjes Milosavljevic [16](#), M. Vreeswijk [117](#), N.K. Vu [144b,144a](#), R. Vuillermet [37](#), O. Vujanovic [102](#), I. Vukotic [40](#), I.K. Vyas [35](#), J.F. Wack [33](#), S. Wada [163](#), C. Wagner¹⁴⁹, J.M. Wagner [18a](#), W. Wagner [177](#), S. Wahdan [177](#), H. Wahlberg [92](#), C.H. Waits [123](#), J. Walder [137](#), R. Walker [111](#), K. Walkingshaw Pass⁵⁹, W. Walkowiak [147](#), A. Wall [131](#), E.J. Wallin [100](#), T. Wamorkar [18a](#), A. Wang [62](#), A.Z. Wang [139](#), C. Wang [102](#), C. Wang [11](#), H. Wang [18a](#), J. Wang [64c](#), P. Wang [103](#), P. Wang [98](#), R. Wang [61](#), R. Wang [6](#), S.M. Wang [154](#), S. Wang [14](#), T. Wang [62](#), T. Wang [62](#), W.T. Wang [80](#), W. Wang [14](#), X. Wang [168](#), X. Wang [144a](#), X. Wang [48](#), Y. Wang [114a](#), Y. Wang [62](#), Z. Wang [108](#), Z. Wang [144b](#), Z. Wang [108](#), C. Wanotayaroj [84](#), A. Warburton [106](#), A.L. Warnerbring [147](#), N. Warrack [59](#), S. Waterhouse [97](#), A.T. Watson [21](#), H. Watson [52](#), M.F. Watson [21](#), E. Watton [59](#), G. Watts [142](#), B.M. Waugh [98](#), J.M. Webb [54](#), C. Weber [30](#), H.A. Weber [19](#), M.S. Weber [20](#), S.M. Weber [63a](#), C. Wei [62](#), Y. Wei [54](#), A.R. Weidberg [129](#), E.J. Weik [120](#), J. Weingarten [49](#), C. Weiser [54](#), C.J. Wells [48](#), T. Wenaus [30](#), B. Wendland [49](#), T. Wengler [37](#), N.S. Wenke¹¹², N. Wermes [25](#), M. Wessels [63a](#), A.M. Wharton [93](#), A.S. White [61](#), A. White [8](#), M.J. White [1](#), D. Whiteson [165](#), L. Wickremasinghe [127](#), W. Wiedenmann [176](#), M. WIELERS [137](#), R. Wierda [150](#), C. WIGLESWORTH [43](#), H.G. Wilkens [37](#), J.J.H. Wilkinson [33](#), D.M. Williams [42](#), H.H. Williams¹³¹, S. Williams [33](#), S. Willocq [105](#), B.J. Wilson [103](#), D.J. Wilson [103](#), P.J. Windischhofer [40](#), F.I. Winkel [31](#), F. Winklmeier [126](#), B.T. Winter [54](#), M. Wittgen¹⁴⁹, M. Wobisch [99](#), T. Wojtkowski⁶⁰, Z. Wolffs [117](#), J. Wollrath³⁷, M.W. Wolter [87](#), H. Wolters [133a,133c](#), M.C. Wong¹³⁹, E.L. Woodward [42](#), S.D. Worm [48](#), B.K. Wosiek [87](#), K.W. Woźniak [87](#), S. Wozniowski [55](#), K. Wraight [59](#), C. Wu [161](#), C. Wu [21](#), J. Wu [159](#), M. Wu [114b](#), M. Wu [116](#), S.L. Wu [176](#), S. Wu [14](#), X. Wu [62](#), Y. Wu [62](#), Z. Wu [4](#), J. Wuerzinger [112](#), T.R. Wyatt [103](#), B.M. Wynne [52](#), S. Xella [43](#), L. Xia [114a](#), M. Xia [15](#), M. Xie [62](#), A. Xiong [126](#), J. Xiong [18a](#), D. Xu [14](#), H. Xu [62](#), L. Xu [62](#), R. Xu [131](#), T. Xu [108](#), Y. Xu [142](#), Z. Xu [52](#), Z. Xu^{114a}, R. Xue [132](#), B. Yabsley [153](#), S. Yacoob [34a](#), Y. Yamaguchi [84](#), E. Yamashita [159](#), H. Yamauchi [163](#), T. Yamazaki [18a](#), Y. Yamazaki [85](#), S. Yan [59](#), Z. Yan [105](#), H.J. Yang [144a,144b](#), H.T. Yang [62](#), S. Yang [62](#), T. Yang [64c](#), X. Yang [37](#), X. Yang [14](#), Y. Yang [159](#), Y. Yang⁶², W-M. Yao [18a](#), C.L. Yardley [152](#), J. Ye [14](#), S. Ye [30](#), X. Ye [62](#), Y. Yeh [98](#), I. Yeletsikh [39](#), B. Yeo [18b](#), M.R. Yexley [98](#), T.P. Yildirim [129](#), P. Yin [42](#), K. Yorita [174](#), C.J.S. Young [37](#), C. Young [149](#), N.D. Young¹²⁶, Y. Yu [62](#), J. Yuan [14,114c](#), M. Yuan [108](#), R. Yuan [144b,144a](#), L. Yue [98](#), M. Zaazoua [62](#), B. Zabinski [87](#), I. Zahir [36a](#), A. Zaio^{57b,57a}, Z.K. Zak [87](#), T. Zakareishvili [169](#), S. Zambito [56](#), J.A. Zamora Saa [140d](#), J. Zang [159](#), R. Zanzottera [71a,71b](#), O. Zaplatilek [135](#), C. Zeitnitz [177](#), H. Zeng [14](#), J.C. Zeng [168](#), D.T. Zenger Jr [27](#), O. Zenin [38](#), T. Ženiš [29a](#), S. Zenz [96](#), D. Zerwas [66](#), M. Zhai [14,114c](#), D.F. Zhang [145](#), G. Zhang [14](#), J. Zhang [143a](#), J. Zhang [6](#), K. Zhang [14,114c](#), L. Zhang [62](#), L. Zhang [114a](#), P. Zhang [14,114c](#), R. Zhang [114a](#), S. Zhang [91](#), T. Zhang [159](#), Y. Zhang [142](#), Y. Zhang [98](#), Y. Zhang [62](#), Y. Zhang [114a](#), Z. Zhang [143a](#), Z. Zhang [66](#), H. Zhao [142](#), T. Zhao [143a](#), Y. Zhao [35](#), Z. Zhao [62](#), Z. Zhao [62](#), A. Zhemchugov [39](#),

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