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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

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JHEP10(2025)054

Contents

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 $pp \to \tau\bar{\tau}$ 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

[1] ATLAS 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}.

JHEP10(2025)054

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 calorimetery [45], and were primarily collected with a trigger requiring a hadronically decaying τ-lepton with $p_{\mathrm{T}} > 80$ GeV and another with $p_{\mathrm{T}} > 60$ 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 $p_{\mathrm{T}} > 90$ 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 $p_{\mathrm{T}} > 28$ 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 $Z \to ee$ 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 $Z \to \tau\tau$ 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 $p_{\text{T}} < 60\,\text{GeV}$ and $|\eta| < 2.5$ that are identified as not being associated with the event's primary vertex, defined as the vertex with the highest $\sum p_{\text{T}}^2$ 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 $p_{\text{T}} < 60\,\text{GeV}$ 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 $p_{\text{T}} > 25\,\text{GeV}$ 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 $p_{\text{T}} > 7\,\text{GeV}$, 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 $p_{\text{T}} > 7\,\text{GeV}$ 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

JHEP10(2025)054

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} parameter[2] set to 1.5 m_{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

[2]The 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 $gg \to VV$ 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 ($H \to \tau\tau$) 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
$H \to \tau\tau$	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].

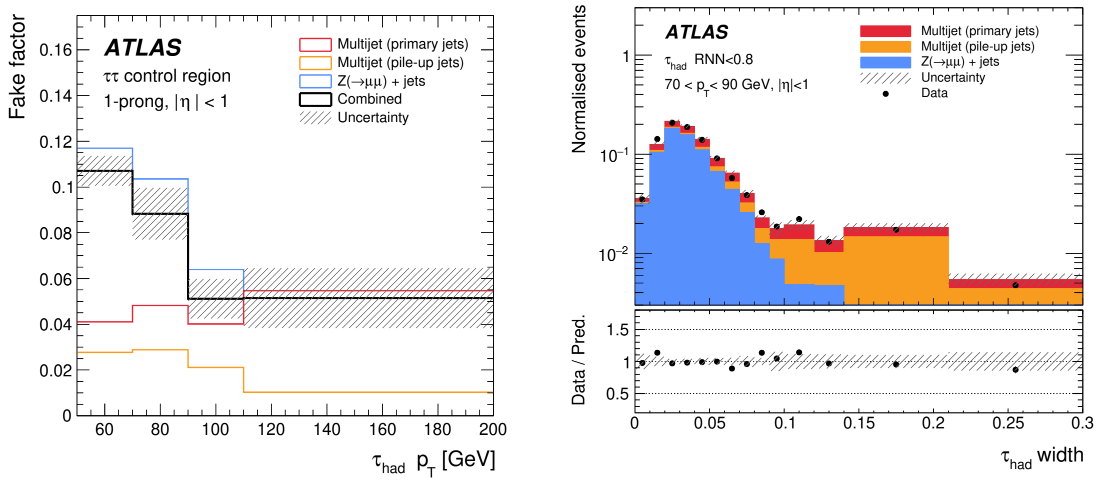
4.2 Misreconstructed τ_{had} background

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 $W(\to \tau\nu)$+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 RNN < 0.8. The extrapolation to the selection region is performed using a fake factor, defined as the ratio of misreconstructed jets satisfying RNN > 0.8 to those with 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 $Z(\to \mu\mu)$+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



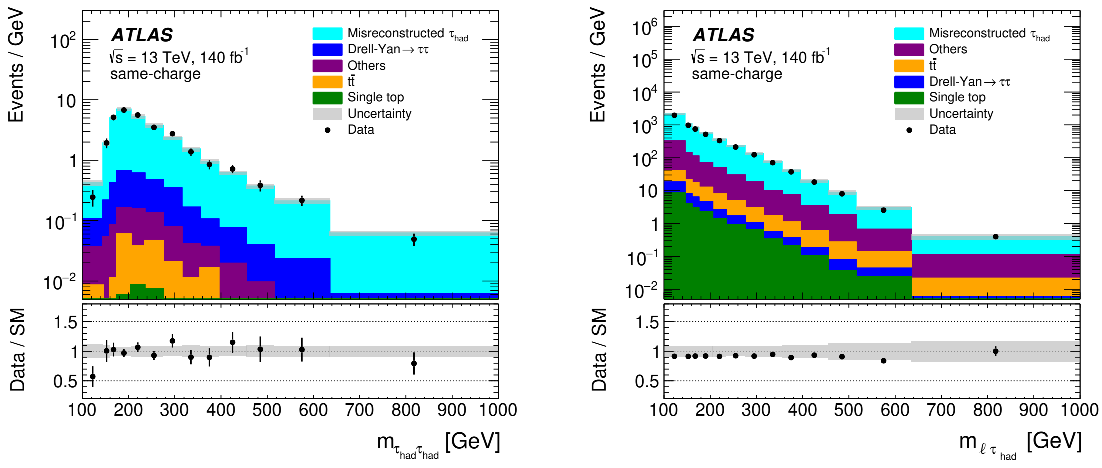
(a) (b)

Figure 1. (a) The fake factor as a function of τ_{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 RNN < 0.8 and one with RNN > 0.8, where the object with 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 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 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.

JHEP10(2025)054



(a) (b)

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 $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ 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 $p_{\mathrm{T}} > 20$ 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 $p_{\mathrm{T}} > 90$ GeV, and the other is required to have $p_{\mathrm{T}} > 60$ GeV. They are required to have opposite signs, and their visible components are used to build the particle-level $m_{\tau\tau}^{\mathrm{vis}}$. 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 τ_{had} τ_{had} invariant mass is shown in figure 3. The detector-level data are compared to the SM prediction consisting of the MC-estimated

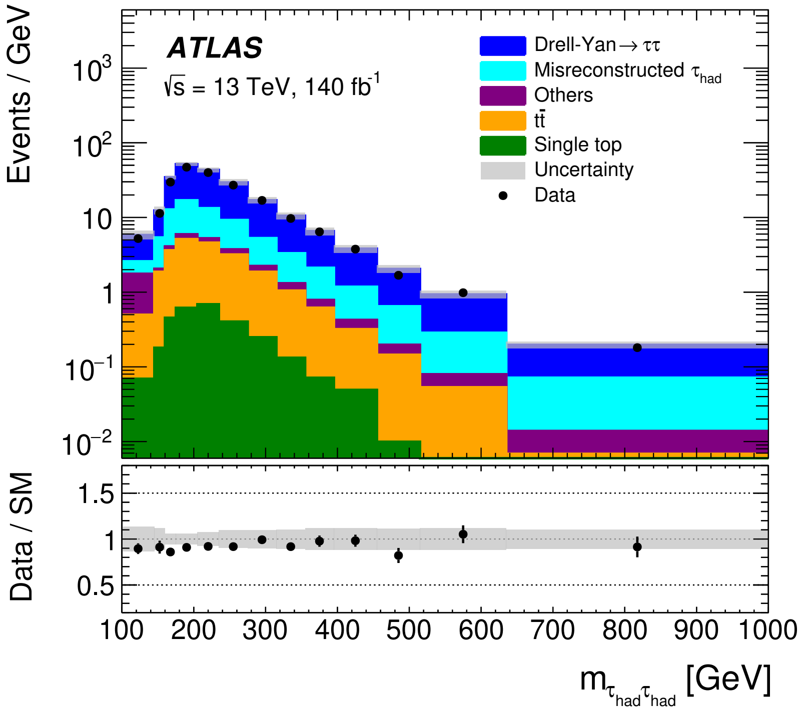


Figure 3. The τ_{had} τ_{had} visible invariant mass in the region of the measurement, before background subtraction and correction for detector effects.

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 $m_{\tau\tau}^{\mathrm{vis}}$. 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 interations 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 $m_{\tau\tau}^{\mathrm{vis}} = 150\,\mathrm{GeV}$, 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

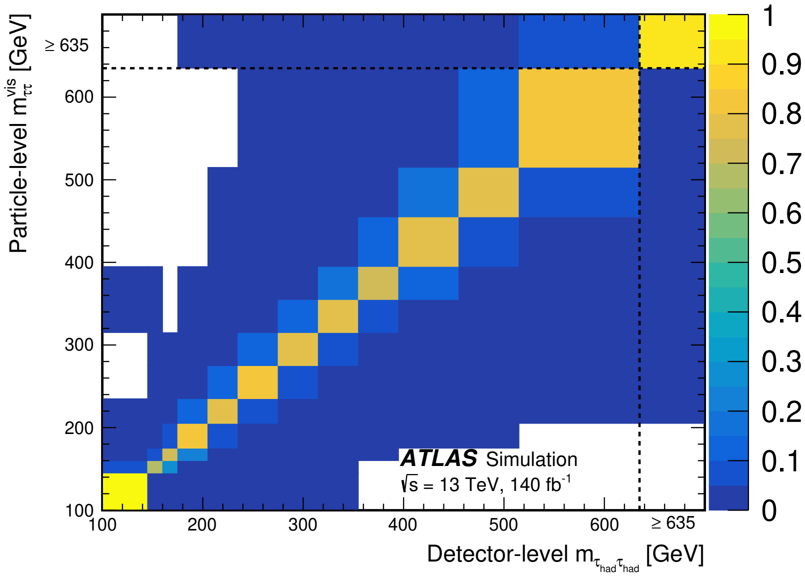


Figure 4. The nominal transfer matrix, showing the probability of an event from a fiducial $m_{\tau\tau}^{\text{vis}}$ bin to be reconstructed at detector-level in a given bin of $\tau_{\text{had}}\tau_{\text{had}}$ invariant mass.

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 $m_{\tau\tau}^{\text{vis}} > 200\,\text{GeV}$.

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.

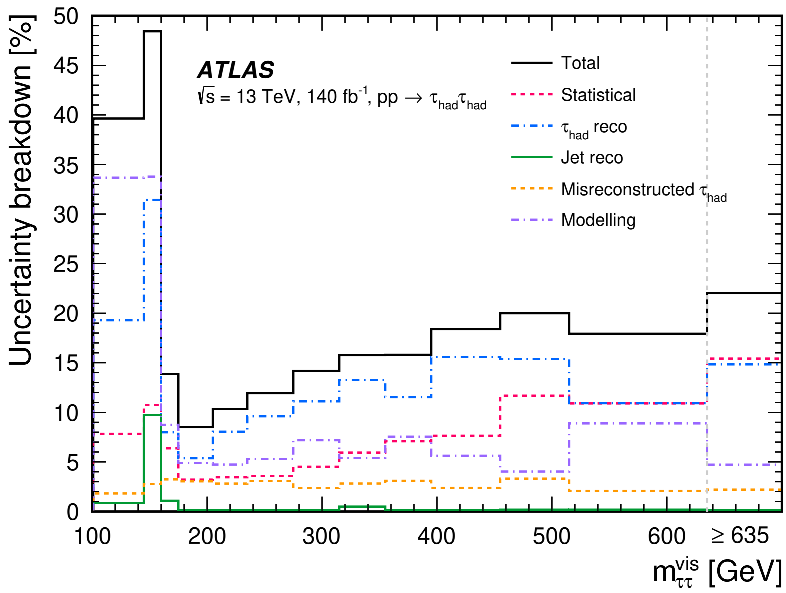


Figure 5. Uncertainty breakdown for the $m_{\tau\tau}^{\rm vis}$ differential cross-section measurement.

5.3 Results

The measured cross-section is shown in figure 6. It peaks at $m_{\tau\tau}^{\rm vis} \approx 200$ 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 $m_{\tau\tau}^{\rm vis} > 300$ 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

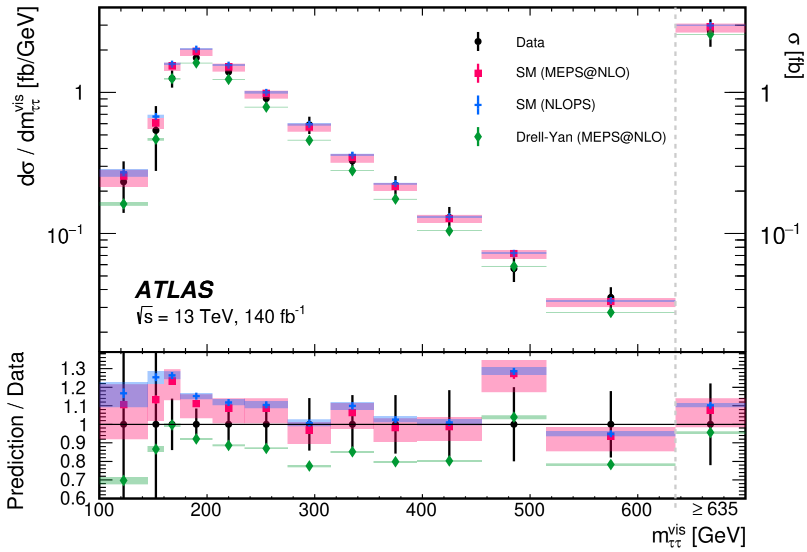


Figure 6. Unfolded fiducial cross-section, differential in $m_{\tau\tau}^{\text{vis}}$, compared with SM predictions from MEPS@NLO (SHERPA 2.2.11) and NLOPS (POWHEG BOX +PYTHIA 8), where all SM processes that contribute significantly to the cross-section are considered. The curve labelled 'Drell-Yan (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 Lagrangrian of an EFT respecting the Standard Model gauge symmetries can be expressed as:

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

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 $pp \to \tau\bar{\tau}$ 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.

JHEP10(2025)054

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]:

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

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]:

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

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

JHEP10(2025)054

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}	$(\bar{\mu}\gamma^\mu \mu)(\bar{e}\gamma^\mu e)$
$c_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{l}\sigma^i\gamma^\mu l)$
$c_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l)$
$c_{H\tau}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{\tau}\gamma^\mu \tau)$
$c_{\tau W}$	$(\bar{l}\sigma^{\mu\nu}\tau)\sigma^i H W^i_{\mu\nu}$
$c_{\tau B}$	$(\bar{l}\sigma^{\mu\nu}\tau) H B_{\mu\nu}$
$c_{\tau Z}$	$(\bar{l}\sigma^{\mu\nu}\tau)\sigma^i H(c_W\sigma^i W^i_{\mu\nu} + s_W B_{\mu\nu})$
$c_{\tau\gamma}$	$(\bar{l}\sigma^{\mu\nu}\tau)\sigma^i H(-s_W\sigma^i W^i_{\mu\nu} + c_W B_{\mu\nu})$

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.

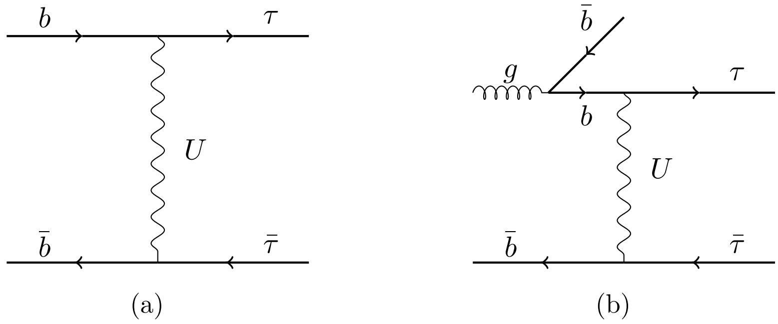


Figure 7. The leading non-resonant diagrams for an initial state of (a) $b\bar{b}$ or (b) $g\bar{b}$ and a final state of (a) $\tau\bar{\tau}$ or (b) $\tau\bar{\tau}\bar{b}$.

JHEP10(2025)054

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, $\sigma \propto (\beta^{i3}_{L,R})^2/m_U^2$ for interference and $\sigma \propto (\beta^{i3}_{L,R})^4/m_U^4$ for the pure-BSM contribution. Weights are included for the scenarios preferred by the B-hadron anomalies, $\beta^{33}_R = -\beta^{33}_L$ and $\beta^{33}_L \neq 0$, with other couplings equal to zero. Additional weights correspond to scenarios of pure right-handed couplings, $\beta^{33}_R \neq 0$, and left-handed couplings between second-generation quarks and third-generation leptons, $\beta^{23}_L \neq 0$.

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

$$\Delta\mathcal{L} = \lambda \bar{b}^C_R \tilde{S}_1 \tau_R + \text{h.c.}, \tag{6.3}$$

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]:

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

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].

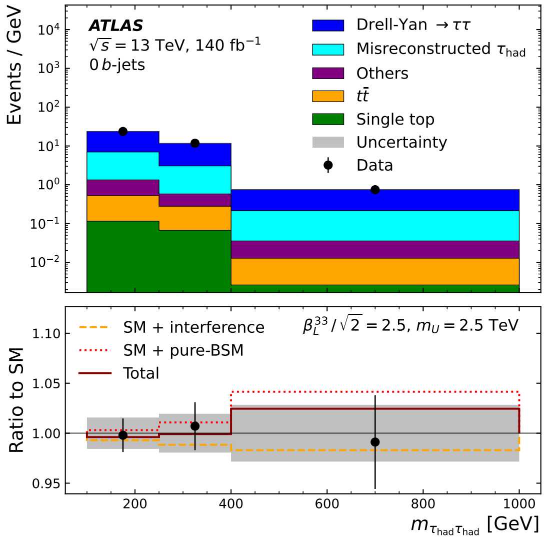
6.5 Results

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.

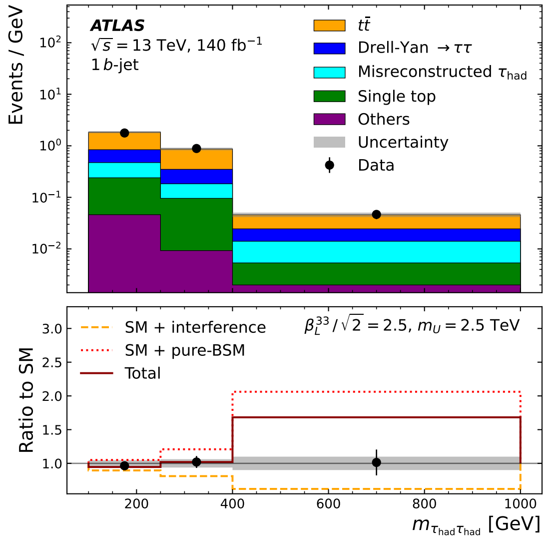
The results of the likelihood fits for individual SMEFT coefficients are given in table 3; fits to the interference-only signal ('linear'), as well as fits using both the interference and BSM terms ('linear + quad.'), are shown. The interference term dominates the sensitivity to all coefficients except $c_{\tau B}$, $c_{\tau W}$, $c_{\tau Z}$, 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

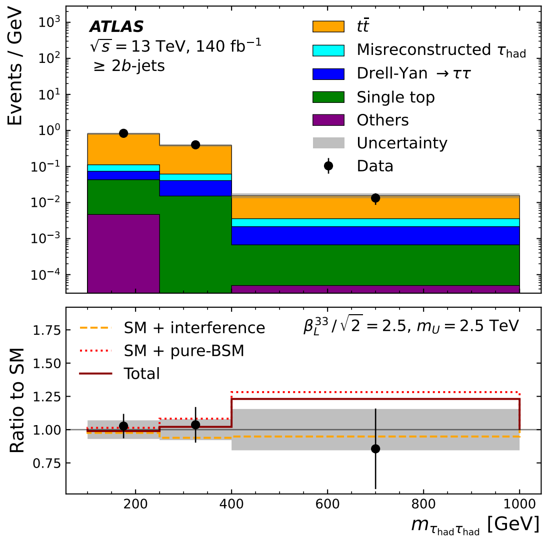
[3] In the previous versions of Contur [140, 141], no signal fit was performed. The current version, Contur 3.1, uses Spey [142] to obtain the best-fit signal.



(a)



(b)



(c)

Figure 8. The background-only post-fit $\tau_{\rm had}\tau_{\rm had}$ 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}	$-0.02^{+0.21}_{-0.21}$	$-0.02^{+0.21}_{-0.21}$
$c_{q\tau}$	$0.01^{+0.07}_{-0.08}$	$0.01^{+0.07}_{-0.16}$
$c_{\tau u}$	$0.01^{+0.04}_{-0.04}$	$0.01^{+0.04}_{-0.04}$
$c_{\tau d}$	$0.07^{+0.32}_{-0.25}$	$0.07^{+0.32}_{-0.25}$
$c_{ll}^{(1)}$	$-1.1^{+1.1}_{-1.1}$	$-1.0^{+1.1}_{-1.1}$
$c_{Hl}^{(3)}$	$0.7^{+0.8}_{-0.8}$	$0.7^{+0.8}_{-0.8}$
$c_{Hl}^{(1)}$	$-1.7^{+1.6}_{-1.6}$	$-1.5^{+1.6}_{-1.6}$
$c_{H\tau}$	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 $\Lambda = 1\,\text{TeV}$ 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 $\gamma\gamma \to \tau\bar{\tau}$ 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},

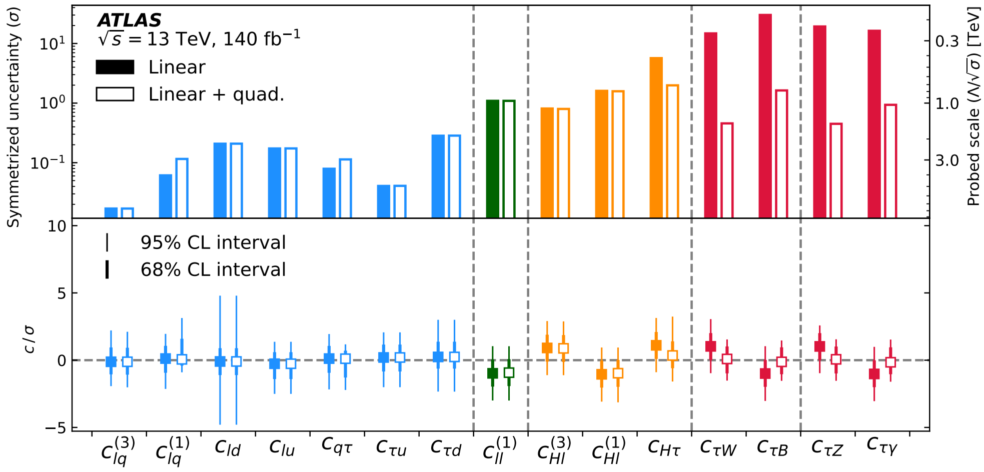


Figure 9. The results of likelihood fits for individual coupling coefficients using only the first-order expansion of the coupling ('linear') or the first-order and partial second-order contributions to the cross-section ('linear + quad.'). The upper panel illustrates the symmetrized 1σ uncertainty in each coupling coefficient at a scale of $\Lambda = 1\,\text{TeV}$ (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.

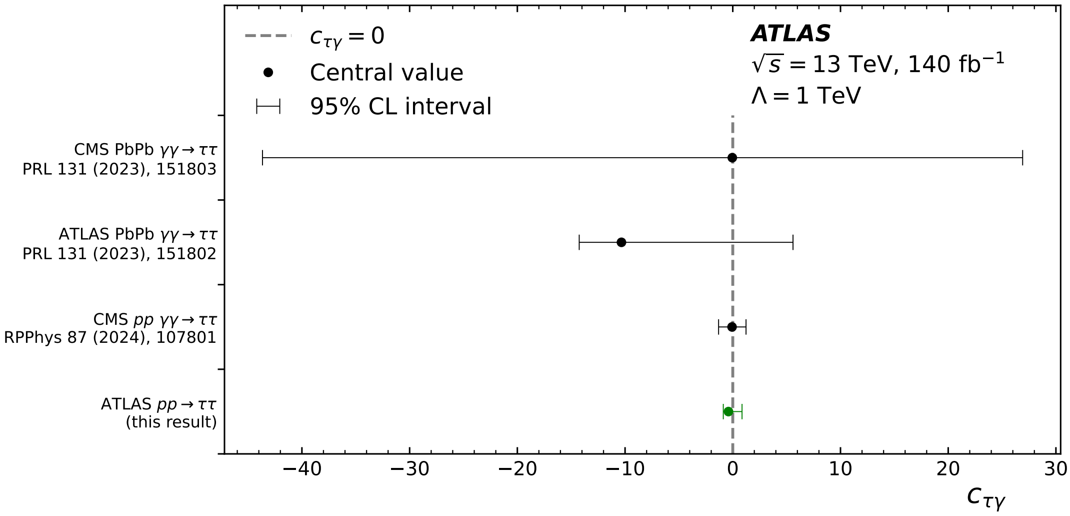
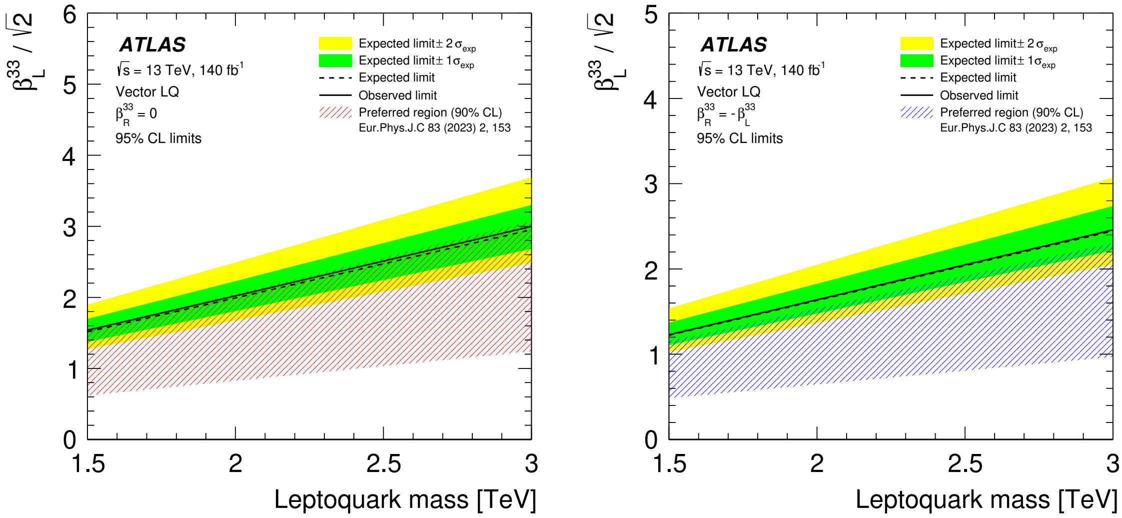


Figure 10. Comparison of central values and confidence intervals on $c_{\tau\gamma}$ from this measurement and measurements probing the τ-lepton anomalous magnetic moment [143–145].

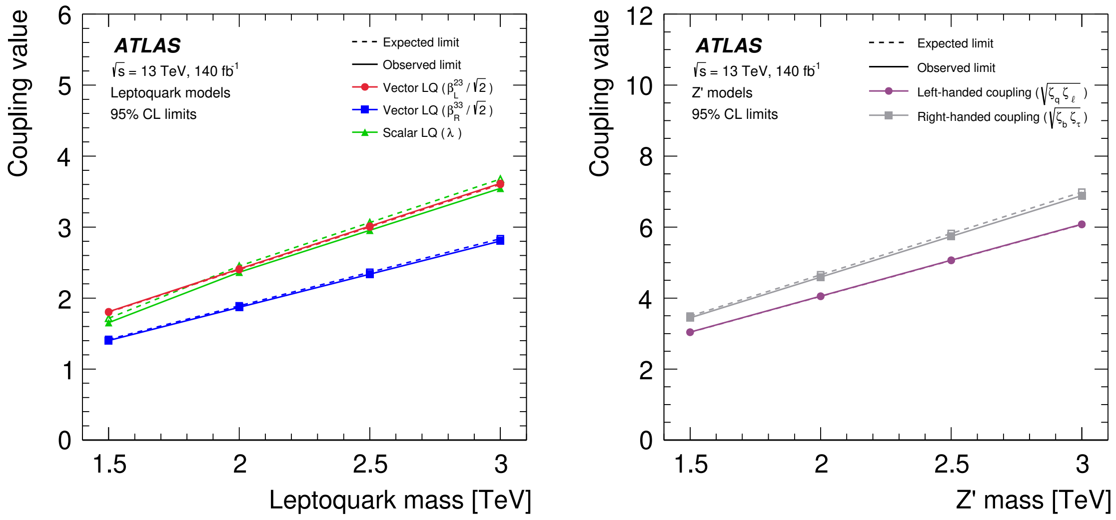
JHEP10(2025)054



(a) (b)

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.



(a) (b)

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.

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References

[1] E598 collaboration, *Experimental observation of a heavy particle J*, Phys. Rev. Lett. **33** (1974) 1404 [INSPIRE].

[2] SLAC-SP-017 collaboration, *Discovery of a narrow resonance in e^+e^- annihilation*, Phys. Rev. Lett. **33** (1974) 1406 [INSPIRE].

[3] E288 collaboration, *Observation of a dimuon resonance at 9.5 GeV in 400 GeV proton-nucleus collisions*, Phys. Rev. Lett. **39** (1977) 252 [INSPIRE].

[4] UA1 collaboration, *Experimental observation of lepton pairs of invariant mass around 95 GeV/c^2 at the CERN SPS collider*, Phys. Lett. B **126** (1983) 398 [INSPIRE].

[5] UA2 collaboration, *Evidence for $Z^0 \to e^+e^-$ at the CERN $\bar{p}p$ collider*, Phys. Lett. B **129** (1983) 130 [INSPIRE].

[6] CMS collaboration, *Measurement of the Drell–Yan forward-backward asymmetry and of the effective leptonic weak mixing angle in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett. B* **866** (2025) 139526 [arXiv:2408.07622] [INSPIRE].

[7] ATLAS collaboration, *Measurement of the forward-backward asymmetry of electron and muon pair-production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *JHEP* **09** (2015) 049 [arXiv:1503.03709] [INSPIRE].

[8] CDF and D0 collaborations, *Tevatron run II combination of the effective leptonic electroweak mixing angle*, *Phys. Rev. D* **97** (2018) 112007 [arXiv:1801.06283] [INSPIRE].

[9] ATLAS collaboration, *Determination of the parton distribution functions of the proton from ATLAS measurements of differential $W^\pm$ and Z boson production in association with jets*, *JHEP* **07** (2021) 223 [arXiv:2101.05095] [INSPIRE].

[10] CMS collaboration, *Measurement of the differential and double-differential Drell-Yan cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **12** (2013) 030 [arXiv:1310.7291] [INSPIRE].

[11] D0 collaboration, *Measurement of the shape of the boson rapidity distribution for $p\bar{p} \to Z/\gamma^* \to e^+e^- + X$ events produced at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. D* **76** (2007) 012003 [hep-ex/0702025] [INSPIRE].

[12] CDF collaboration, *Measurement of $d\sigma/dy$ of Drell-Yan e^+e^- pairs in the Z mass region from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Lett. B* **692** (2010) 232 [arXiv:0908.3914] [INSPIRE].

[13] ATLAS collaboration, *Search for high-mass dilepton resonances using 139 fb^{-1} of pp collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Lett. B* **796** (2019) 68 [arXiv:1903.06248] [INSPIRE].

[14] CMS collaboration, *Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s} = 13$ TeV*, *JHEP* **07** (2021) 208 [arXiv:2103.02708] [INSPIRE].

[15] U. Haisch, L. Schnell and S. Schulte, *Drell-Yan production in third-generation gauge vector leptoquark models at NLO+PS in QCD*, *JHEP* **02** (2023) 070 [arXiv:2209.12780] [INSPIRE].

[16] ATLAS collaboration, *Search for heavy Higgs bosons decaying into two tau leptons with the ATLAS detector using pp collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. Lett.* **125** (2020) 051801 [arXiv:2002.12223] [INSPIRE].

[17] J. Davighi and G. Isidori, *Non-universal gauge interactions addressing the inescapable link between Higgs and flavour*, *JHEP* **07** (2023) 147 [arXiv:2303.01520] [INSPIRE].

[18] B. Capdevila, A. Crivellin and J. Matias, *Review of semileptonic B anomalies*, *Eur. Phys. J. ST* **1** (2023) 20 [arXiv:2309.01311] [INSPIRE].

[19] HFLAV collaboration, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021*, *Phys. Rev. D* **107** (2023) 052008 [arXiv:2206.07501] [INSPIRE].

[20] LHCb collaboration, *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$*, *Phys. Rev. Lett.* **115** (2015) 111803 [*Erratum ibid.* **115** (2015) 159901] [arXiv:1506.08614] [INSPIRE].

[21] BaBar collaboration, *Measurement of an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons*, *Phys. Rev. D* **88** (2013) 072012 [arXiv:1303.0571] [INSPIRE].

[22] Belle collaboration, *Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle*, *Phys. Rev. D* **92** (2015) 072014 [arXiv:1507.03233] [INSPIRE].

[23] BELLE collaboration, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ with one-prong hadronic τ decays at Belle*, *Phys. Rev. D* **97** (2018) 012004 [arXiv:1709.00129] [INSPIRE].

[24] BELLE collaboration, *Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method*, *Phys. Rev. Lett.* **124** (2020) 161803 [arXiv:1910.05864] [INSPIRE].

[25] LHCb collaboration, *Test of lepton flavor universality by the measurement of the $B^0 \to D^{*-} \tau^+ \nu_\tau$ branching fraction using three-prong τ decays*, *Phys. Rev. D* **97** (2018) 072013 [arXiv:1711.02505] [INSPIRE].

[26] LHCb collaboration, *Test of lepton flavor universality using $B^0 \to D^{*-} \tau^+ \nu_\tau$ decays with hadronic τ channels*, *Phys. Rev. D* **108** (2023) 012018 [*Erratum ibid.* **109** (2024) 119902] [arXiv:2305.01463] [INSPIRE].

[27] LHCb collaboration, *Measurement of $Z \to \tau^+ \tau^-$ production in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **09** (2018) 159 [arXiv:1806.05008] [INSPIRE].

[28] CMS collaboration, *Measurement of the inclusive Z cross section via decays to tau pairs in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **08** (2011) 117 [arXiv:1104.1617] [INSPIRE].

[29] ATLAS collaboration, *Measurement of the $Z \to \tau\tau$ cross section with the ATLAS detector*, *Phys. Rev. D* **84** (2011) 112006 [arXiv:1108.2016] [INSPIRE].

[30] ATLAS collaboration, *Measurement of the double-differential high-mass Drell-Yan cross section in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *JHEP* **08** (2016) 009 [arXiv:1606.01736] [INSPIRE].

[31] ATLAS collaboration, *Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Phys. Lett. B* **725** (2013) 223 [arXiv:1305.4192] [INSPIRE].

[32] CMS collaboration, *Measurement of the differential Drell-Yan cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **12** (2019) 059 [arXiv:1812.10529] [INSPIRE].

[33] CMS collaboration, *Measurements of differential and double-differential Drell-Yan cross sections in proton-proton collisions at 8 TeV*, *Eur. Phys. J. C* **75** (2015) 147 [arXiv:1412.1115] [INSPIRE].

[34] CMS collaboration, *Measurement of the Drell-Yan cross section in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **10** (2011) 007 [arXiv:1108.0566] [INSPIRE].

[35] ATLAS collaboration, *Search for additional heavy neutral Higgs and gauge bosons in the ditau final state produced in 36 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **01** (2018) 055 [arXiv:1709.07242] [INSPIRE].

[36] CMS collaboration, *Search for heavy resonances decaying to tau lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **02** (2017) 048 [arXiv:1611.06594] [INSPIRE].

[37] ATLAS collaboration, *Search for leptoquarks decaying into the $b\tau$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **10** (2023) 001 [arXiv:2305.15962] [INSPIRE].

[38] CMS collaboration, *Search for a third-generation leptoquark coupled to a τ lepton and a b quark through single, pair, and nonresonant production in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **05** (2024) 311 [arXiv:2308.07826] [INSPIRE].

[39] ATLAS collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, 2008 *JINST* **3** S08003 [INSPIRE].

[40] L. Evans and P. Bryant, *LHC machine*, 2008 *JINST* **3** S08001 [INSPIRE].

[41] ATLAS collaboration, *Performance of the ATLAS trigger system in 2015*, *Eur. Phys. J. C* **77** (2017) 317 [arXiv:1611.09661] [INSPIRE].

[42] ATLAS collaboration, *Software and computing for run 3 of the ATLAS experiment at the LHC*, *Eur. Phys. J. C* **85** (2025) 234 [arXiv:2404.06335] [INSPIRE].

[43] ATLAS collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **83** (2023) 982 [arXiv:2212.09379] [INSPIRE].

[44] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, 2018 *JINST* **13** P07017 [INSPIRE].

[45] ATLAS collaboration, *ATLAS data quality operations and performance for 2015–2018 data-taking*, 2020 *JINST* **15** P04003 [arXiv:1911.04632] [INSPIRE].

[46] ATLAS collaboration, *Estimation of backgrounds from jets misidentified as τ-leptons using the universal fake factor method with the ATLAS detector*, arXiv:2502.04156 [INSPIRE].

[47] M. Cacciari, G.P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [arXiv:0802.1189] [INSPIRE].

[48] ATLAS collaboration, *Identification of hadronic tau lepton decays using neural networks in the ATLAS experiment*, ATL-PHYS-PUB-2019-033, CERN, Geneva, Switzerland (2019).

[49] ATLAS collaboration, *Reconstruction, energy calibration, and identification of hadronically decaying tau leptons in the ATLAS experiment for run-2 of the LHC*, ATL-PHYS-PUB-2015-045, CERN, Geneva, Switzerland (2015).

[50] ATLAS collaboration, *Measurement of the tau lepton reconstruction and identification performance in the ATLAS experiment using pp collisions at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2017-029, CERN, Geneva, Switzerland (2017).

[51] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [arXiv:1111.6097] [INSPIRE].

[52] ATLAS collaboration, *Jet reconstruction and performance using particle flow with the ATLAS detector*, *Eur. Phys. J. C* **77** (2017) 466 [arXiv:1703.10485] [INSPIRE].

[53] ATLAS collaboration, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC run 1*, *Eur. Phys. J. C* **77** (2017) 490 [arXiv:1603.02934] [INSPIRE].

[54] ATLAS collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 581 [arXiv:1510.03823] [INSPIRE].

[55] ATLAS collaboration, *Identification and rejection of pile-up jets at high pseudorapidity with the ATLAS detector*, *Eur. Phys. J. C* **77** (2017) 580 [*Erratum ibid.* **77** (2017) 712] [arXiv:1705.02211] [INSPIRE].

[56] ATLAS collaboration, *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Rev. D* **96** (2017) 072002 [arXiv:1703.09665] [INSPIRE].

[57] ATLAS collaboration, *ATLAS flavour-tagging algorithms for the LHC run 2 pp collision dataset*, *Eur. Phys. J. C* **83** (2023) 681 [arXiv:2211.16345] [INSPIRE].

[58] ATLAS collaboration, *ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **79** (2019) 970 [arXiv:1907.05120] [INSPIRE].

JHEP10(2025)054

[59] ATLAS collaboration, *Electron and photon efficiencies in LHC run 2 with the ATLAS experiment*, JHEP **05** (2024) 162 [arXiv:2308.13362] [INSPIRE].

[60] ATLAS collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton-proton collision data*, 2019 JINST **14** P12006 [arXiv:1908.00005] [INSPIRE].

[61] ATLAS collaboration, *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at* $\sqrt{s} = 13$ *TeV*, Eur. Phys. J. C **76** (2016) 292 [arXiv:1603.05598] [INSPIRE].

[62] ATLAS collaboration, *Measurements of Higgs boson production cross-sections in the* $H \to \tau^+\tau^-$ *decay channel in pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, JHEP **08** (2022) 175 [arXiv:2201.08269] [INSPIRE].

[63] SHERPA collaboration, *Event generation with Sherpa 2.2*, SciPost Phys. **7** (2019) 034 [arXiv:1905.09127] [INSPIRE].

[64] T. Gleisberg and S. Höche, *Comix, a new matrix element generator*, JHEP **12** (2008) 039 [arXiv:0808.3674] [INSPIRE].

[65] F. Buccioni et al., *OpenLoops 2*, Eur. Phys. J. C **79** (2019) 866 [arXiv:1907.13071] [INSPIRE].

[66] F. Cascioli, P. Maierhöfer and S. Pozzorini, *Scattering amplitudes with OpenLoops*, Phys. Rev. Lett. **108** (2012) 111601 [arXiv:1111.5206] [INSPIRE].

[67] A. Denner, S. Dittmaier and L. Hofer, *Collier: a fortran-based Complex One-Loop LIbrary in Extended Regularizations*, Comput. Phys. Commun. **212** (2017) 220 [arXiv:1604.06792] [INSPIRE].

[68] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani-Seymour dipole factorisation*, JHEP **03** (2008) 038 [arXiv:0709.1027] [INSPIRE].

[69] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *A critical appraisal of NLO+PS matching methods*, JHEP **09** (2012) 049 [arXiv:1111.1220] [INSPIRE].

[70] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *QCD matrix elements + parton showers: the NLO case*, JHEP **04** (2013) 027 [arXiv:1207.5030] [INSPIRE].

[71] S. Catani, F. Krauss, R. Kuhn and B.R. Webber, *QCD matrix elements + parton showers*, JHEP **11** (2001) 063 [hep-ph/0109231] [INSPIRE].

[72] S. Höche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*, JHEP **05** (2009) 053 [arXiv:0903.1219] [INSPIRE].

[73] NNPDF collaboration, *Parton distributions for the LHC run II*, JHEP **04** (2015) 040 [arXiv:1410.8849] [INSPIRE].

[74] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **11** (2004) 040 [hep-ph/0409146] [INSPIRE].

[75] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, JHEP **11** (2007) 070 [arXiv:0709.2092] [INSPIRE].

[76] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043 [arXiv:1002.2581] [INSPIRE].

[77] S. Alioli, P. Nason, C. Oleari and E. Re, *NLO vector-boson production matched with shower in POWHEG*, JHEP **07** (2008) 060 [arXiv:0805.4802] [INSPIRE].

[78] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852 [arXiv:0710.3820] [INSPIRE].

[79] ATLAS collaboration, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, JHEP **09** (2014) 145 [arXiv:1406.3660] [INSPIRE].

[80] H.-L. Lai et al., *New parton distributions for collider physics*, Phys. Rev. D **82** (2010) 074024 [arXiv:1007.2241] [INSPIRE].

[81] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, JHEP **07** (2002) 012 [hep-ph/0201195] [INSPIRE].

[82] P. Golonka and Z. Was, *PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays*, Eur. Phys. J. C **45** (2006) 97 [hep-ph/0506026] [INSPIRE].

[83] N. Davidson, T. Przedzinski and Z. Was, *PHOTOS interface in C++: technical and physics documentation*, Comput. Phys. Commun. **199** (2016) 86 [arXiv:1011.0937] [INSPIRE].

[84] D.J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A **462** (2001) 152 [INSPIRE].

[85] ATLAS collaboration, *Studies on top-quark Monte Carlo modelling for Top2016*, ATL-PHYS-PUB-2016-020, CERN, Geneva, Switzerland (2016).

[86] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].

[87] ATLAS collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, ATL-PHYS-PUB-2014-021, CERN, Geneva, Switzerland (2014).

[88] R.D. Ball et al., *Parton distributions with LHC data*, Nucl. Phys. B **867** (2013) 244 [arXiv:1207.1303] [INSPIRE].

[89] M. Bähr et al., *Herwig++ physics and manual*, Eur. Phys. J. C **58** (2008) 639 [arXiv:0803.0883] [INSPIRE].

[90] J. Bellm et al., *Herwig 7.0/Herwig++ 3.0 release note*, Eur. Phys. J. C **76** (2016) 196 [arXiv:1512.01178] [INSPIRE].

[91] L.A. Harland-Lang, A.D. Martin, P. Motylinski and R.S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, Eur. Phys. J. C **75** (2015) 204 [arXiv:1412.3989] [INSPIRE].

[92] S. Frixione et al., *Single-top hadroproduction in association with a W boson*, JHEP **07** (2008) 029 [arXiv:0805.3067] [INSPIRE].

[93] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP **07** (2014) 079 [arXiv:1405.0301] [INSPIRE].

[94] K. Hamilton, P. Nason, E. Re and G. Zanderighi, *NNLOPS simulation of Higgs boson production*, JHEP **10** (2013) 222 [arXiv:1309.0017] [INSPIRE].

[95] K. Hamilton, P. Nason and G. Zanderighi, *Finite quark-mass effects in the NNLOPS POWHEG+MiNLO Higgs generator*, JHEP **05** (2015) 140 [arXiv:1501.04637] [INSPIRE].

[96] J. Butterworth et al., *PDF4LHC recommendations for LHC run II*, J. Phys. G **43** (2016) 023001 [arXiv:1510.03865] [INSPIRE].

[97] LHC Higgs Cross Section Working Group collaboration, *Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector*, CERN Yellow Rep. Monogr. **2** (2017) 1 [arXiv:1610.07922] [INSPIRE].

[98] C. Anastasiou et al., *High precision determination of the gluon fusion Higgs boson cross-section at the LHC*, JHEP **05** (2016) 058 [arXiv:1602.00695] [INSPIRE].

[99] C. Anastasiou et al., *Higgs boson gluon-fusion production in QCD at three loops*, Phys. Rev. Lett. **114** (2015) 212001 [arXiv:1503.06056] [INSPIRE].

[100] F. Dulat, A. Lazopoulos and B. Mistlberger, *iHixs 2 — inclusive Higgs cross sections*, Comput. Phys. Commun. **233** (2018) 243 [arXiv:1802.00827] [INSPIRE].

[101] R.V. Harlander and K.J. Ozeren, *Finite top mass effects for hadronic Higgs production at next-to-next-to-leading order*, JHEP **11** (2009) 088 [arXiv:0909.3420] [INSPIRE].

[102] R.V. Harlander and K.J. Ozeren, *Top mass effects in Higgs production at next-to-next-to-leading order QCD: virtual corrections*, Phys. Lett. B **679** (2009) 467 [arXiv:0907.2997] [INSPIRE].

[103] R.V. Harlander, H. Mantler, S. Marzani and K.J. Ozeren, *Higgs production in gluon fusion at next-to-next-to-leading order QCD for finite top mass*, Eur. Phys. J. C **66** (2010) 359 [arXiv:0912.2104] [INSPIRE].

[104] A. Pak, M. Rogal and M. Steinhauser, *Finite top quark mass effects in NNLO Higgs boson production at LHC*, JHEP **02** (2010) 025 [arXiv:0911.4662] [INSPIRE].

[105] S. Actis, G. Passarino, C. Sturm and S. Uccirati, *NLO electroweak corrections to Higgs boson production at hadron colliders*, Phys. Lett. B **670** (2008) 12 [arXiv:0809.1301] [INSPIRE].

[106] S. Actis, G. Passarino, C. Sturm and S. Uccirati, *NNLO computational techniques: the cases $H \to \gamma\gamma$ and $H \to gg$*, Nucl. Phys. B **811** (2009) 182 [arXiv:0809.3667] [INSPIRE].

[107] M. Bonetti, K. Melnikov and L. Tancredi, *Higher order corrections to mixed QCD-EW contributions to Higgs boson production in gluon fusion*, Phys. Rev. D **97** (2018) 056017 [*Erratum ibid.* **97** (2018) 099906] [arXiv:1801.10403] [INSPIRE].

[108] A. Djouadi, J. Kalinowski and M. Spira, *HDECAY: a program for Higgs boson decays in the standard model and its supersymmetric extension*, Comput. Phys. Commun. **108** (1998) 56 [hep-ph/9704448] [INSPIRE].

[109] M. Spira, *QCD effects in Higgs physics*, Fortsch. Phys. **46** (1998) 203 [hep-ph/9705337] [INSPIRE].

[110] A. Djouadi, M.M. Mühlleitner and M. Spira, *Decays of supersymmetric particles: the program SUSY-HIT (SUspect-SdecaY-Hdecay-InTerface)*, *Acta Phys. Polon. B* **38** (2007) 635 [hep-ph/0609292] [INSPIRE].

[111] A. Bredenstein, A. Denner, S. Dittmaier and M.M. Weber, *Radiative corrections to the semileptonic and hadronic Higgs-boson decays $H \to WW/ZZ \to 4$ fermions*, JHEP **02** (2007) 080 [hep-ph/0611234] [INSPIRE].

[112] A. Bredenstein, A. Denner, S. Dittmaier and M.M. Weber, *Precise predictions for the Higgs-boson decay $H \to WW/ZZ \to 4$ leptons*, Phys. Rev. D **74** (2006) 013004 [hep-ph/0604011] [INSPIRE].

[113] A. Bredenstein, A. Denner, S. Dittmaier and M.M. Weber, *Precision calculations for the Higgs decays $H \to ZZ/WW \to 4$ leptons*, Nucl. Phys. B Proc. Suppl. **160** (2006) 131 [hep-ph/0607060] [INSPIRE].

[114] M.J. Baker, J. Fuentes-Martín, G. Isidori and M. König, *High-p_T signatures in vector-leptoquark models*, Eur. Phys. J. C **79** (2019) 334 [arXiv:1901.10480] [INSPIRE].

[115] C. Bierlich et al., *A comprehensive guide to the physics and usage of PYTHIA 8.3*, SciPost Phys. Codeb. **2022** (2022) 8 [arXiv:2203.11601] [INSPIRE].

[116] ATLAS collaboration, *Measurements of the production cross-section for a Z boson in association with b- or c-jets in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C **84** (2024) 984 [arXiv:2403.15093] [INSPIRE].

[117] I. Brivio, *SMEFTsim 3.0 — a practical guide*, JHEP **04** (2021) 073 [arXiv:2012.11343] [INSPIRE].

[118] ATLAS collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie-Landshoff diffractive model*, ATL-PHYS-PUB-2016-017, CERN, Geneva, Switzerland (2016).

[119] ATLAS collaboration, *The ATLAS simulation infrastructure*, Eur. Phys. J. C **70** (2010) 823 [arXiv:1005.4568] [INSPIRE].

[120] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250 [INSPIRE].

[121] ATLAS collaboration, *ATLAS measurements of the properties of jets for boosted particle searches*, Phys. Rev. D **86** (2012) 072006 [arXiv:1206.5369] [INSPIRE].

[122] ATLAS collaboration, *Measurements of differential cross-sections in four-lepton events in 13 TeV proton-proton collisions with the ATLAS detector*, JHEP **07** (2021) 005 [arXiv:2103.01918] [INSPIRE].

[123] ATLAS collaboration, *Differential cross-sections for events with missing transverse momentum and jets measured with the ATLAS detector in 13 TeV proton-proton collisions*, JHEP **08** (2024) 223 [arXiv:2403.02793] [INSPIRE].

[124] G. D'Agostini, *A multidimensional unfolding method based on Bayes' theorem*, Nucl. Instrum. Meth. A **362** (1995) 487 [INSPIRE].

[125] ATLAS collaboration, *Evaluating statistical uncertainties and correlations using the bootstrap method*, ATL-PHYS-PUB-2021-011, CERN, Geneva, Switzerland (2021).

[126] E. Maguire, L. Heinrich and G. Watt, *HEPData: a repository for high energy physics data*, J. Phys. Conf. Ser. **898** (2017) 102006 [arXiv:1704.05473] [INSPIRE].

[127] C. Bierlich et al., *Robust independent validation of experiment and theory: Rivet version 3*, SciPost Phys. **8** (2020) 026 [arXiv:1912.05451] [INSPIRE].

[128] B. Fuks et al., *Probing the Weinberg operator at colliders*, Phys. Rev. D **103** (2021) 115014 [arXiv:2012.09882] [INSPIRE].

[129] ATLAS collaboration, *Interpretations of the ATLAS measurements of Higgs boson production and decay rates and differential cross-sections in pp collisions at $\sqrt{s} = 13$ TeV*, JHEP **11** (2024) 097 [arXiv:2402.05742] [INSPIRE].

[130] R. Escribano and E. Masso, *New bounds on the magnetic and electric moments of the tau lepton*, Phys. Lett. B **301** (1993) 419 [INSPIRE].

[131] L. Beresford and J. Liu, *New physics and tau $g - 2$ using LHC heavy ion collisions*, Phys. Rev. D **102** (2020) 113008 [*Erratum ibid.* **106** (2022) 039902] [arXiv:1908.05180] [INSPIRE].

[132] L. Beresford, S. Clawson and J. Liu, *Strategy to measure tau $g - 2$ via photon fusion in LHC proton collisions*, Phys. Rev. D **110** (2024) 092016 [arXiv:2403.06336] [INSPIRE].

[133] U. Haisch, L. Schnell and J. Weiss, *LHC tau-pair production constraints on a_τ and d_τ*, *SciPost Phys.* **16** (2024) 048 [arXiv:2307.14133] [INSPIRE].

[134] I. Doršner et al., *Physics of leptoquarks in precision experiments and at particle colliders*, *Phys. Rept.* **641** (2016) 1 [arXiv:1603.04993] [INSPIRE].

[135] L. Heinrich, M. Feickert, G. Stark and K. Cranmer, *pyhf: pure-Python implementation of HistFactory statistical models*, *J. Open Source Softw.* **6** (2021) 2823 [INSPIRE].

[136] K. Cranmer and A. Held, *Building and steering binned template fits with cabinetry*, *EPJ Web Conf.* **251** (2021) 03067 [INSPIRE].

[137] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth. A* **434** (1999) 435 [hep-ex/9902006] [INSPIRE].

[138] A.L. Read, *Presentation of search results: the CL_s technique*, *J. Phys. G* **28** (2002) 2693 [INSPIRE].

[139] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [*Erratum ibid.* **73** (2013) 2501] [arXiv:1007.1727] [INSPIRE].

[140] CONTUR collaboration, *Testing new physics models with global comparisons to collider measurements: the Contur toolkit*, *SciPost Phys. Core* **4** (2021) 013 [arXiv:2102.04377] [INSPIRE].

[141] CONTUR collaboration, *Constraining new physics with collider measurements of standard model signatures*, *JHEP* **03** (2017) 078 [arXiv:1606.05296] [INSPIRE].

[142] J.Y. Araz, *Spey: smooth inference for reinterpretation studies*, *SciPost Phys.* **16** (2024) 032 [arXiv:2307.06996] [INSPIRE].

[143] ATLAS collaboration, *Observation of the $\gamma\gamma \to \tau\tau$ process in Pb+Pb collisions and constraints on the τ-lepton anomalous magnetic moment with the ATLAS detector*, *Phys. Rev. Lett.* **131** (2023) 151802 [arXiv:2204.13478] [INSPIRE].

[144] CMS collaboration, *Observation of $\gamma\gamma \to \tau\tau$ in proton-proton collisions and limits on the anomalous electromagnetic moments of the τ lepton*, *Rept. Prog. Phys.* **87** (2024) 107801 [arXiv:2406.03975] [INSPIRE].

[145] CMS collaboration, *Observation of τ lepton pair production in ultraperipheral lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Rev. Lett.* **131** (2023) 151803 [arXiv:2206.05192] [INSPIRE].

[146] ATLAS collaboration, *ATLAS computing acknowledgements*, ATL-SOFT-PUB-2025-001, CERN, Geneva, Switzerland (2025).

JHEP10(2025)054

The ATLAS collaboration

G. Aad[104], E. Aakvaag[17], B. Abbott[123], S. Abdelhameed[119a], K. Abeling[55], N.J. Abicht[49], S.H. Abidi[30], M. Aboelela[45], A. Aboulhorma[36e], H. Abramowicz[157], Y. Abulaiti[120], B.S. Acharya[69a,69b,n], A. Ackermann[63a], C. Adam Bourdarios[4], L. Adamczyk[86a], S.V. Addepalli[149], M.J. Addison[103], J. Adelman[118], A. Adiguzel[22c], T. Adye[137], A.A. Affolder[139], Y. Afik[40], M.N. Agaras[13], A. Aggarwal[102], C. Agheorghiesei[28c], F. Ahmadov[39,ae], S. Ahuja[97], X. Ai[143b], G. Aielli[76a,76b], A. Aikot[169], M. Ait Tamlihat[36e], B. Aitbenchikh[36a], M. Akbiyik[102], T.P.A. Åkesson[100], A.V. Akimov[151], D. Akiyama[174], N.N. Akolkar[25], S. Aktas[22a], G.L. Alberghi[24b], J. Albert[171], P. Albicocco[53], G.L. Albouy[60], S. Alderweireldt[52], Z.L. Alegria[124], M. Aleksa[37], I.N. Aleksandrov[39], C. Alexa[28b], T. Alexopoulos[10], F. Alfonsi[24b], M. Algren[56], M. Alhroob[173], B. Ali[135], H.M.J. Ali[93,x], S. Ali[32], S.W. Alibocus[94], M. Aliev[34c], G. Alimonti[71a], W. Alkakhi[55], C. Allaire[66], B.M.M. Allbrooke[152], J.S. Allen[103], J.F. Allen[52], P.P. Allport[21], A. Aloisio[72a,72b], F. Alonso[92], C. Alpigiani[142], Z.M.K. Alsolami[93], A. Alvarez Fernandez[102], M. Alves Cardoso[56], M.G. Alviggi[72a,72b], M. Aly[103], Y. Amaral Coutinho[83b], A. Ambler[106], C. Amelung[37], M. Amerl[103], C.G. Ames[111], T. Amezza[130], D. Amidei[108], B. Amini[54], K. Amirie[161], A. Amirkhanov[39], S.P. Amor Dos Santos[133a], K.R. Amos[169], D. Amperiadou[158], S. An[84], C. Anastopoulos[145], T. Andeen[11], J.K. Anders[94], A.C. Anderson[59], A. Andreazza[71a,71b], S. Angelidakis[9], A. Angerami[42], A.V. Anisenkov[39], A. Annovi[74a], C. Antel[56], E. Antipov[151], M. Antonelli[53], F. Anulli[75a], M. Aoki[84], T. Aoki[159], M.A. Aparo[152], L. Aperio Bella[48], M. Apicella[31], C. Appelt[157], A. Apyan[27], S.J. Arbiol Val[87], C. Arcangeletti[53], A.T.H. Arce[51], J-F. Arguin[110], S. Argyropoulos[158], J.-H. Arling[48], O. Arnaez[4], H. Arnold[151], G. Artoni[75a,75b], H. Asada[113], K. Asai[121], S. Asai[159], S. Asatryan[179], N.A. Asbah[37], R.A. Ashby Pickering[173], A.M. Aslam[97], K. Assamagan[30], R. Astalos[29a], K.S.V. Astrand[100], S. Atashi[165], R.J. Atkin[34a], H. Atmani[36f], P.A. Atmasiddha[131], K. Augsten[135], A.D. Auriol[41], V.A. Austrup[103], G. Avolio[37], K. Axiotis[56], G. Azuelos[110,ai], D. Babal[29b], H. Bachacou[138], K. Bachas[158,r], A. Bachiu[35], E. Bachmann[50], M.J. Backes[63a], A. Badea[40], T.M. Baer[108], P. Bagnaia[75a,75b], M. Bahmani[19], D. Bahner[54], K. Bai[126], J.T. Baines[137], L. Baines[96], O.K. Baker[178], E. Bakos[16], D. Bakshi Gupta[8], L.E. Balabram Filho[83b], V. Balakrishnan[123], R. Balasubramanian[4], E.M. Baldin[38], P. Balek[86a], E. Ballabene[24b,24a], F. Balli[138], L.M. Baltes[63a], W.K. Balunas[33], J. Balz[102], I. Bamwidhi[119b], E. Banas[87], M. Bandieramonte[132], A. Bandyopadhyay[25], S. Bansal[25], L. Barak[157], M. Barakat[48], E.L. Barberio[107], D. Barberis[18b], M. Barbero[104], M.Z. Barel[117], T. Barillari[112], M-S. Barisits[37], T. Barklow[149], P. Baron[136], D.A. Baron Moreno[103], A. Baroncelli[62], A.J. Barr[129], J.D. Barr[98], F. Barreiro[101], J. Barreiro Guimarães da Costa[14], M.G. Barros Teixeira[133a], S. Barsov[38], F. Bartels[63a], R. Bartoldus[149], A.E. Barton[93], P. Bartos[29a], A. Basan[102], M. Baselga[49], S. Bashiri[87], A. Bassalat[66,b], M.J. Basso[162a], S. Bataju[45], R. Bate[170], R.L. Bates[59], S. Batlamous[101], M. Battaglia[139], D. Battulga[19], M. Bauce[75a,75b], M. Bauer[79], P. Bauer[25], L.T. Bayer[48], L.T. Bazzano Hurrell[31], J.B. Beacham[112], T. Beau[130], J.Y. Beaucamp[92], P.H. Beauchemin[164], P. Bechtle[25], H.P. Beck[20,q], K. Becker[173], A.J. Beddall[82], V.A. Bednyakov[39], C.P. Bee[151],

JHEP10(2025)054

L.J. Beemster[16], M. Begalli[83d], M. Begel[30], J.K. Behr[48], J.F. Beirer[37], F. Beisiegel[25], M. Belfkir[119b], G. Bella[157], L. Bellagamba[24b], A. Bellerive[35], C.D. Bellgraph[68], P. Bellos[21], K. Beloborodov[38], D. Benchekroun[36a], F. Bendebba[36a], Y. Benhammou[157], K.C. Benkendorfer[61], L. Beresford[48], M. Beretta[53], E. Bergeaas Kuutmann[167], N. Berger[4], B. Bergmann[135], J. Beringer[18a], G. Bernardi[5], C. Bernius[149], F.U. Bernlochner[25], F. Bernon[37], A. Berrocal Guardia[13], T. Berry[97], P. Berta[136], A. Berthold[50], A. Berti[133a], R. Bertrand[104], S. Bethke[112], A. Betti[75a,75b], A.J. Bevan[96], L. Bezio[56], N.K. Bhalla[54], S. Bharthuar[112], S. Bhatta[151], P. Bhattarai[149], Z.M. Bhatti[120], K.D. Bhide[54], V.S. Bhopatkar[124], R.M. Bianchi[132], G. Bianco[24b,24a], O. Biebel[111], M. Biglietti[77a], C.S. Billingsley[45], Y. Bimgdi[36f], M. Bindi[55], A. Bingham[177], A. Bingul[22b], C. Bini[75a,75b], G.A. Bird[33], M. Birman[175], M. Biros[136], S. Biryukov[152], T. Bisanz[49], E. Bisceglie[24b,24a], J.P. Biswal[137], D. Biswas[147], I. Bloch[48], A. Blue[59], U. Blumenschein[96], J. Blumenthal[102], V.S. Bobrovnikov[39], L. Boccardo[57b,57a], M. Boehler[54], B. Boehm[172], D. Bogavac[13], A.G. Bogdanchikov[38], L.S. Boggia[130], V. Boisvert[97], P. Bokan[37], T. Bold[86a], M. Bomben[5], M. Bona[96], M. Boonekamp[138], A.G. Borbély[59], I.S. Bordulev[38], G. Borissov[93], D. Bortoletto[129], D. Boscherini[24b], M. Bosman[13], K. Bouaouda[36a], N. Bouchhar[169], L. Boudet[4], J. Boudreau[132], E.V. Bouhova-Thacker[93], D. Boumediene[41], R. Bouquet[57b,57a], A. Boveia[122], J. Boyd[37], D. Boye[30], I.R. Boyko[39], L. Bozianu[56], J. Bracinik[21], N. Brahimi[4], G. Brandt[177], O. Brandt[33], B. Brau[105], J.E. Brau[126], R. Brener[175], L. Brenner[117], R. Brenner[167], S. Bressler[175], G. Brianti[78a,78b], D. Britton[59], D. Britzger[112], I. Brock[25], R. Brock[109], G. Brooijmans[42], A.J. Brooks[68], E.M. Brooks[162b], E. Brost[30], L.M. Brown[171,162a], L.E. Bruce[61], T.L. Bruckler[129], P.A. Bruckman de Renstrom[87], B. Brüers[48], A. Bruni[24b], G. Bruni[24b], D. Brunner[47a,47b], M. Bruschi[24b], N. Bruscino[75a,75b], T. Buanes[17], Q. Buat[142], D. Buchin[112], A.G. Buckley[59], O. Bulekov[82], B.A. Bullard[149], S. Burdin[94], C.D. Burgard[49], A.M. Burger[91], B. Burghgrave[8], O. Burlayenko[54], J. Burleson[168], J.C. Burzynski[148], E.L. Busch[42], V. Büscher[102], P.J. Bussey[59], J.M. Butler[26], C.M. Buttar[59], J.M. Butterworth[98], W. Buttinger[137], C.J. Buxo Vazquez[109], A.R. Buzykaev[39], S. Cabrera Urbán[169], L. Cadamuro[66], D. Caforio[58], H. Cai[132], Y. Cai[24b,114c,24a], Y. Cai[114a], V.M.M. Cairo[37], O. Cakir[3a], N. Calace[37], P. Calafiura[18a], G. Calderini[130], P. Calfayan[35], G. Callea[59], L.P. Caloba[83b], D. Calvet[41], S. Calvet[41], R. Camacho Toro[130], S. Camarda[37], D. Camarero Munoz[27], P. Camarri[76a,76b], C. Camincher[171], M. Campanelli[98], A. Camplani[43], V. Canale[72a,72b], A.C. Canbay[3a], E. Canonero[97], J. Cantero[169], Y. Cao[168], F. Capocasa[27], M. Capua[44b,44a], A. Carbone[71a,71b], R. Cardarelli[76a], J.C.J. Cardenas[8], M.P. Cardiff[27], G. Carducci[44b,44a], T. Carli[37], G. Carlino[72a], J.I. Carlotto[13], B.T. Carlson[132,s], E.M. Carlson[171], J. Carmignani[94], L. Carminati[71a,71b], A. Carnelli[4], M. Carnesale[37], S. Caron[116], E. Carquin[140g], I.B. Carr[107], S. Carrá[73a,73b], G. Carratta[24b,24a], A.M. Carroll[126], M.P. Casado[13,i], P. Casolaro[72a,72b], M. Caspar[48], F.L. Castillo[4], L. Castillo Garcia[13], V. Castillo Gimenez[169], N.F. Castro[133a,133e], A. Catinaccio[37], J.R. Catmore[128], T. Cavaliere[4], V. Cavaliere[30], L.J. Caviedes Betancourt[23b], E. Celebi[82], S. Cella[37], V. Cepaitis[56], K. Cerny[125], A.S. Cerqueira[83a], A. Cerri[74a,74b,al], L. Cerrito[76a,76b], F. Cerutti[18a], B. Cervato[71a,71b], A. Cervelli[24b], G. Cesarini[53], S.A. Cetin[82],

JHEP10(2025)054

P.M. Chabrillat[130], R. Chakkappai[66], S. Chakraborty[173], J. Chan[18a], W.Y. Chan[159], J.D. Chapman[33], E. Chapon[138], B. Chargeishvili[155b], D.G. Charlton[21], C. Chauhan[136], Y. Che[114a], S. Chekanov[6], S.V. Chekulaev[162a], G.A. Chelkov[39,a], B. Chen[157], B. Chen[171], H. Chen[114a], H. Chen[30], J. Chen[144a], J. Chen[148], M. Chen[129], S. Chen[89], S.J. Chen[114a], X. Chen[144a], X. Chen[15,ah], Z. Chen[62], C.L. Cheng[176], H.C. Cheng[64a], S. Cheong[149], A. Cheplakov[39], E. Cherepanova[117], R. Cherkaoui El Moursli[36e], E. Cheu[7], K. Cheung[65], L. Chevalier[138], V. Chiarella[53], G. Chiarelli[74a], G. Chiodini[70a], A.S. Chisholm[21], A. Chitan[28b], M. Chitishvili[169], M.V. Chizhov[39,t], K. Choi[11], Y. Chou[142], E.Y.S. Chow[116], K.L. Chu[175], M.C. Chu[64a], X. Chu[14,114c], Z. Chubinidze[53], J. Chudoba[134], J.J. Chwastowski[87], D. Cieri[112], K.M. Ciesla[86a], V. Cindro[95], A. Ciocio[18a], F. Cirotto[72a,72b], Z.H. Citron[175], M. Citterio[71a], D.A. Ciubotaru[28b], A. Clark[56], P.J. Clark[52], N. Clarke Hall[98], C. Clarry[161], S.E. Clawson[48], C. Clement[47a,47b], Y. Coadou[104], M. Cobal[69a,69c], A. Coccaro[57b], R.F. Coelho Barrue[133a], R. Coelho Lopes De Sa[105], S. Coelli[71a], L.S. Colangeli[161], B. Cole[42], P. Collado Soto[101], J. Collot[60], R. Coluccia[70a,70b], P. Conde Muiño[133a,133g], M.P. Connell[34c], S.H. Connell[34c], E.I. Conroy[129], M. Contreras Cossio[11], F. Conventi[72a,aj], A.M. Cooper-Sarkar[129], L. Corazzina[75a,75b], F.A. Corchia[24b,24a], A. Cordeiro Oudot Choi[142], L.D. Corpe[41], M. Corradi[75a,75b], F. Corriveau[106,ac], A. Cortes-Gonzalez[159], M.J. Costa[169], F. Costanza[4], D. Costanzo[145], B.M. Cote[122], J. Couthures[4], G. Cowan[97], K. Cranmer[176], L. Cremer[49], D. Cremonini[24b,24a], S. Crépé-Renaudin[60], F. Crescioli[130], T. Cresta[73a,73b], M. Cristinziani[147], M. Cristoforetti[78a,78b], V. Croft[117], J.E. Crosby[124], G. Crosetti[44b,44a], A. Cueto[101], H. Cui[98], Z. Cui[7], W.R. Cunningham[59], F. Curcio[169], J.R. Curran[52], M.J. Da Cunha Sargedas De Sousa[57b,57a], J.V. Da Fonseca Pinto[83b], C. Da Via[103], W. Dabrowski[86a], T. Dado[37], S. Dahbi[154], T. Dai[108], D. Dal Santo[20], C. Dallapiccola[105], M. Dam[43], G. D'amen[30], V. D'Amico[111], J. Damp[102], J.R. Dandoy[35], D. Dannheim[37], G. D'anniballe[74a,74b], M. Danninger[148], V. Dao[151], G. Darbo[57b], S.J. Das[30], F. Dattola[48], S. D'Auria[71a,71b], A. D'Avanzo[72a,72b], T. Davidek[136], J. Davidson[173], I. Dawson[96], K. De[8], C. De Almeida Rossi[161], R. De Asmundis[72a], N. De Biase[48], S. De Castro[24b,24a], N. De Groot[116], P. de Jong[117], H. De la Torre[118], A. De Maria[114a], A. De Salvo[75a], U. De Sanctis[76a,76b], F. De Santis[70a,70b], A. De Santo[152], J.B. De Vivie De Regie[60], J. Debevc[95], D.V. Dedovich[39], J. Degens[94], A.M. Deiana[45], J. Del Peso[101], L. Delagrange[130], F. Deliot[138], C.M. Delitzsch[49], M. Della Pietra[72a,72b], D. Della Volpe[56], A. Dell'Acqua[37], L. Dell'Asta[71a,71b], M. Delmastro[4], C.C. Delogu[102], P.A. Delsart[60], S. Demers[178], M. Demichev[39], S.P. Denisov[38], H. Denizli[22a,m], L. D'Eramo[41], D. Derendarz[87], F. Derue[130], P. Dervan[94], A.M. Desai[1], K. Desch[25], F.A. Di Bello[57b,57a], A. Di Ciaccio[76a,76b], L. Di Ciaccio[4], A. Di Domenico[75a,75b], C. Di Donato[72a,72b], A. Di Girolamo[37], G. Di Gregorio[37], A. Di Luca[78a,78b], B. Di Micco[77a,77b], R. Di Nardo[77a,77b], K.F. Di Petrillo[40], M. Diamantopoulou[35], F.A. Dias[117], M.A. Diaz[140a,140b], A.R. Didenko[39], M. Didenko[169], S.D. Diefenbacher[18a], E.B. Diehl[108], S. Díez Cornell[48], C. Diez Pardos[147], C. Dimitriadi[150], A. Dimitrievska[21], A. Dimri[151], J. Dingfelder[25], T. Dingley[129], I-M. Dinu[28b], S.J. Dittmeier[63b], F. Dittus[37], M. Divisek[136], B. Dixit[94], F. Djama[104], T. Djobava[155b], C. Doglioni[103,100], A. Dohnalova[29a], Z. Dolezal[136], K. Domijan[86a], K.M. Dona[40], M. Donadelli[83d],

JHEP10(2025)054

B. Dong[109], J. Donini[41], A. D'Onofrio[72a,72b], M. D'Onofrio[94], J. Dopke[137], A. Doria[72a], N. Dos Santos Fernandes[133a], P. Dougan[103], M.T. Dova[92], A.T. Doyle[59], M.A. Draguet[129], M.P. Drescher[55], E. Dreyer[175], I. Drivas-koulouris[10], M. Drnevich[120], M. Drozdova[56], D. Du[62], T.A. du Pree[117], Z. Duan[114a], M. Dubau[4], F. Dubinin[39], M. Dubovsky[29a], E. Duchovni[175], G. Duckeck[111], P.K. Duckett[98], O.A. Ducu[28b], D. Duda[52], A. Dudarev[37], E.R. Duden[27], M. D'uffizi[103], L. Duflot[66], M. Dührssen[37], I. Duminica[28g], A.E. Dumitriu[28b], M. Dunford[63a], S. Dungs[49], K. Dunne[47a,47b], A. Duperrin[104], H. Duran Yildiz[3a], M. Düren[58], A. Durglishvili[155b], D. Duvnjak[35], G.I. Dyckes[18a], M. Dyndal[86a], B.S. Dziedzic[37], Z.O. Earnshaw[152], G.H. Eberwein[129], B. Eckerova[29a], J.C. Egan[98], S. Eggebrecht[55], E. Egidio Purcino De Souza[83e], G. Eigen[17], K. Einsweiler[18a], T. Ekelof[167], P.A. Ekman[100], S. El Farkh[36b], Y. El Ghazali[62], H. El Jarrari[37], A. El Moussaouy[36a], V. Ellajosyula[167], M. Ellert[167], F. Ellinghaus[177], N. Ellis[37], J. Elmsheuser[30], M. Elsawy[119a], M. Elsing[37], D. Emeliyanov[137], Y. Enari[84], I. Ene[18a], S. Epari[110], D. Ernani Martins Neto[87], F. Ernst[37], M. Errenst[177], M. Escalier[66], C. Escobar[169], E. Etzion[157], G. Evans[133a,133b], H. Evans[68], L.S. Evans[97], A. Ezhilov[38], S. Ezzarqtouni[36a], F. Fabbri[24b,24a], L. Fabbri[24b,24a], G. Facini[98], V. Fadeyev[139], R.M. Fakhrutdinov[38], D. Fakoudis[102], S. Falciano[75a], L.F. Falda Ulhoa Coelho[133a], F. Fallavollita[112], G. Falsetti[44b,44a], J. Faltova[136], C. Fan[168], K.Y. Fan[64b], Y. Fan[14], Y. Fang[14,114c], M. Fanti[71a,71b], M. Faraj[69a,69b], Z. Farazpay[99], A. Farbin[8], A. Farilla[77a], T. Farooque[109], J.N. Farr[178], S.M. Farrington[137,52], F. Fassi[36e], D. Fassouliotis[9], L. Fayard[66], P. Federic[136], P. Federicova[134], O.L. Fedin[38,a], M. Feickert[176], L. Feligioni[104], D.E. Fellers[18a], C. Feng[143a], Z. Feng[117], M.J. Fenton[165], L. Ferencz[48], B. Fernandez Barbadillo[93], P. Fernandez Martinez[67], M.J.V. Fernoux[104], J. Ferrando[93], A. Ferrari[167], P. Ferrari[117,116], R. Ferrari[73a], D. Ferrere[56], C. Ferretti[108], M.P. Fewell[1], D. Fiacco[75a,75b], F. Fiedler[102], P. Fiedler[135], S. Filimonov[39], M.S. Filip[28b,u], A. Filipčič[95], E.K. Filmer[162a], F. Filthaut[116], M.C.N. Fiolhais[133a,133c,c], L. Fiorini[169], W.C. Fisher[109], T. Fitschen[103], P.M. Fitzhugh[138], I. Fleck[147], P. Fleischmann[108], T. Flick[177], M. Flores[34d,ag], L.R. Flores Castillo[64a], L. Flores Sanz De Acedo[37], F.M. Follega[78a,78b], N. Fomin[33], J.H. Foo[161], A. Formica[138], A.C. Forti[103], E. Fortin[37], A.W. Fortman[18a], L. Foster[18a], L. Fountas[9,j], D. Fournier[66], H. Fox[93], P. Francavilla[74a,74b], S. Francescato[61], S. Franchellucci[56], M. Franchini[24b,24a], S. Franchino[63a], D. Francis[37], L. Franco[116], V. Franco Lima[37], L. Franconi[48], M. Franklin[61], G. Frattari[27], Y.Y. Frid[157], J. Friend[59], N. Fritzsche[37], A. Froch[56], D. Froidevaux[37], J.A. Frost[129], Y. Fu[109], S. Fuenzalida Garrido[140g], M. Fujimoto[104], K.Y. Fung[64a], E. Furtado De Simas Filho[83e], M. Furukawa[159], J. Fuster[169], A. Gaa[55], A. Gabrielli[24b,24a], A. Gabrielli[161], P. Gadow[37], G. Gagliardi[57b,57a], L.G. Gagnon[18a], S. Gaid[88b], S. Galantzan[157], J. Gallagher[1], E.J. Gallas[129], A.L. Gallen[167], B.J. Gallop[137], K.K. Gan[122], S. Ganguly[159], Y. Gao[52], A. Garabaglu[142], F.M. Garay Walls[140a,140b], C. García[169], A. Garcia Alonso[117], A.G. Garcia Caffaro[178], J.E. García Navarro[169], M.A. Garcia Ruiz[23b], M. Garcia-Sciveres[18a], G.L. Gardner[131], R.W. Gardner[40], N. Garelli[164], R.B. Garg[149], J.M. Gargan[52], C.A. Garner[161], C.M. Garvey[34a], V.K. Gassmann[164], G. Gaudio[73a], V. Gautam[13], P. Gauzzi[75a,75b], J. Gavranovic[95], I.L. Gavrilenko[133a], A. Gavrilyuk[38], C. Gay[170], G. Gaycken[126], E.N. Gazis[10], A. Gekow[122],

JHEP10(2025)054

C. Gemme[57b], M.H. Genest[60], A.D. Gentry[115], S. George[97], T. Geralis[46], A.A. Gerwin[123], P. Gessinger-Befurt[37], M.E. Geyik[177], M. Ghani[173], K. Ghorbanian[96], A. Ghosal[147], A. Ghosh[165], A. Ghosh[7], B. Giacobbe[24b], S. Giagu[75a,75b], T. Giani[117], A. Giannini[62], S.M. Gibson[97], M. Gignac[139], D.T. Gil[86b], A.K. Gilbert[86a], B.J. Gilbert[42], D. Gillberg[35], G. Gilles[117], D.M. Gingrich[2,ai], M.P. Giordani[69a,69c], P.F. Giraud[138], G. Giugliarelli[69a,69c], D. Giugni[71a], F. Giuli[76a,76b], I. Gkialas[9,j], L.K. Gladilin[38], C. Glasman[101], M. Glazewska[20], R.M. Gleason[165], G. Glemža[48], M. Glisic[126], I. Gnesi[44b], Y. Go[30], M. Goblirsch-Kolb[37], B. Gocke[49], D. Godin[110], B. Gokturk[22a], S. Goldfarb[107], T. Golling[56], M.G.D. Gololo[34c], D. Golubkov[38], J.P. Gombas[109], A. Gomes[133a,133b], G. Gomes Da Silva[147], A.J. Gomez Delegido[169], R. Gonçalo[133a], L. Gonella[21], A. Gongadze[155c], F. Gonnella[21], J.L. Gonski[149], R.Y. González Andana[52], S. González de la Hoz[169], M.V. Gonzalez Rodrigues[48], R. Gonzalez Suarez[167], S. Gonzalez-Sevilla[56], L. Goossens[37], B. Gorini[37], E. Gorini[70a,70b], A. Gorišek[95], T.C. Gosart[131], A.T. Goshaw[51], M.I. Gostkin[39], S. Goswami[124], C.A. Gottardo[37], S.A. Gotz[111], M. Gouighri[36b], A.G. Goussiou[142], N. Govender[34c], R.P. Grabarczyk[129], I. Grabowska-Bold[86a], K. Graham[35], E. Gramstad[128], S. Grancagnolo[70a,70b], C.M. Grant[1], P.M. Gravila[28f], F.G. Gravili[70a,70b], H.M. Gray[18a], M. Greco[112], M.J. Green[1], C. Grefe[25], A.S. Grefsrud[17], I.M. Gregor[48], K.T. Greif[165], P. Grenier[149], S.G. Grewe[112], A.A. Grillo[139], K. Grimm[32], S. Grinstein[13,y], J.-F. Grivaz[66], E. Gross[175], J. Grosse-Knetter[55], L. Guan[108], G. Guerrieri[37], R. Guevara[128], R. Gugel[102], J.A.M. Guhit[108], A. Guida[19], E. Guilloton[173], S. Guindon[37], F. Guo[14,114c], J. Guo[144a], L. Guo[48], L. Guo[114b,w], Y. Guo[108], A. Gupta[49], R. Gupta[132], S. Gupta[27], S. Gurbuz[25], S.S. Gurdasani[48], G. Gustavino[75a,75b], P. Gutierrez[123], L.F. Gutierrez Zagazeta[131], M. Gutsche[50], C. Gutschow[98], C. Gwenlan[129], C.B. Gwilliam[94], E.S. Haaland[128], A. Haas[120], M. Habedank[59], C. Haber[18a], H.K. Hadavand[8], A. Haddad[41], A. Hadef[50], A.I. Hagan[93], J.J. Hahn[147], E.H. Haines[98], M. Haleem[172], J. Haley[124], G.D. Hallewell[104], L. Halser[20], K. Hamano[171], M. Hamer[25], S.E.D. Hammoud[66], E.J. Hampshire[97], J. Han[143a], L. Han[114a], L. Han[62], S. Han[18a], K. Hanagaki[84], M. Hance[139], D.A. Hangal[42], H. Hanif[148], M.D. Hank[131], J.B. Hansen[43], P.H. Hansen[43], D. Harada[56], T. Harenberg[177], S. Harkusha[179], M.L. Harris[105], Y.T. Harris[25], J. Harrison[13], N.M. Harrison[122], P.F. Harrison[173], M.L.E. Hart[98], N.M. Hartman[112], N.M. Hartmann[111], R.Z. Hasan[97,137], Y. Hasegawa[146], F. Haslbeck[129], S. Hassan[17], R. Hauser[109], M. Haviernik[136], C.M. Hawkes[21], R.J. Hawkings[37], Y. Hayashi[159], D. Hayden[109], C. Hayes[108], R.L. Hayes[117], C.P. Hays[129], J.M. Hays[96], H.S. Hayward[94], M. He[14,114c], Y. He[48], Y. He[98], N.B. Heatley[96], V. Hedberg[100], C. Heidegger[54], K.K. Heidegger[54], J. Heilman[35], S. Heim[48], T. Heim[18a], J.G. Heinlein[131], J.J. Heinrich[126], L. Heinrich[112], J. Hejbal[134], M. Helbig[50], A. Held[176], S. Hellesund[17], C.M. Helling[170], S. Hellman[47a,47b], A.M. Henriques Correia[37], H. Herde[100], Y. Hernández Jiménez[151], L.M. Herrmann[25], T. Herrmann[50], G. Herten[54], R. Hertenberger[111], L. Hervas[37], M.E. Hesping[102], N.P. Hessey[162a], J. Hessler[112], M. Hidaoui[36b], N. Hidic[136], E. Hill[161], T.S. Hillersoy[17], S.J. Hillier[21], J.R. Hinds[109], F. Hinterkeuser[25], M. Hirose[127], S. Hirose[163], D. Hirschbuehl[177], T.G. Hitchings[103], B. Hiti[95], J. Hobbs[151], R. Hobincu[28e], N. Hod[175], A.M. Hodges[168], M.C. Hodgkinson[145], B.H. Hodkinson[129], A. Hoecker[37], D.D. Hofer[108], J. Hofer[169], M. Holzbock[37], L.B.A.H. Hommels[33], V. Homsak[129], B.P. Honan[103], J.J. Hong[68], T.M. Hong[132], B.H. Hooberman[168], W.H. Hopkins[6], M.C. Hoppesch[168], Y. Horii[113], M.E. Horstmann[112], S. Hou[154], M.R. Housenga[168], A.S. Howard[95], J. Howarth[59], J. Hoya[6], M. Hrabovsky[125], T. Hryn'ova[4], P.J. Hsu[65], S.-C. Hsu[142], T. Hsu[66], M. Hu[18a], Q. Hu[62], S. Huang[33], X. Huang[14,114c], Y. Huang[136], Y. Huang[114b], Y. Huang[102], Y. Huang[14], Z. Huang[66], Z. Hubacek[135], M. Huebner[25], F. Huegging[25], T.B. Huffman[129], M. Hufnagel Maranha De Faria[83a], C.A. Hugli[48], M. Huhtinen[37], S.K. Huiberts[17], R. Hulsken[106], C.E. Hultquist[18a], N. Huseynov[12,g], J. Huston[109], J. Huth[61], R. Hyneman[7], G. Iacobucci[56], G. Iakovidis[30], L. Iconomidou-Fayard[66], J.P. Iddon[37], P. Iengo[72a,72b], R. Iguchi[159], Y. Iiyama[159], T. Iizawa[159], Y. Ikegami[84], D. Iliadis[158], N. Ilic[161], H. Imam[36a], G. Inacio Goncalves[83d], S.A. Infante Cabanas[140c], T. Ingebretsen Carlson[47a,47b], J.M. Inglis[96], G. Introzzi[73a,73b], M. Iodice[77a], V. Ippolito[75a,75b], R.K. Irwin[94], M. Ishino[159], W. Islam[176], C. Issever[19], S. Istin[22a,an], K. Itabashi[84], H. Ito[174], R. Iuppa[78a,78b], A. Ivina[175], V. Izzo[72a], P. Jacka[134], P. Jackson[1], P. Jain[48], K. Jakobs[54], T. Jakoubek[175], J. Jamieson[59], W. Jang[159], S. Jankovych[136], M. Javurkova[105], P. Jawahar[103], L. Jeanty[126], J. Jejelava[155a,af], P. Jenni[54,f], C.E. Jessiman[35], C. Jia[143a], H. Jia[170], J. Jia[151], X. Jia[14,114c], Z. Jia[114a], C. Jiang[52], Q. Jiang[64b], S. Jiggins[48], M. Jimenez Ortega[169], J. Jimenez Pena[13], S. Jin[114a], A. Jinaru[28b], O. Jinnouchi[141], P. Johansson[145], K.A. Johns[7], J.W. Johnson[139], F.A. Jolly[48], D.M. Jones[152], E. Jones[48], K.S. Jones[8], P. Jones[33], R.W.L. Jones[93], T.J. Jones[94], H.L. Joos[55,37], R. Joshi[122], J. Jovicevic[16], X. Ju[18a], J.J. Junggeburth[37], T. Junkermann[63a], A. Juste Rozas[13,y], M.K. Juzek[87], S. Kabana[140f], A. Kaczmarska[87], M. Kado[112], H. Kagan[122], M. Kagan[149], A. Kahn[131], C. Kahra[102], T. Kaji[159], E. Kajomovitz[156], N. Kakati[175], N. Kakoty[13], I. Kalaitzidou[54], S. Kandel[8], N.J. Kang[139], D. Kar[34h], K. Karava[129], E. Karentzos[25], O. Karkout[117], S.N. Karpov[39], Z.M. Karpova[39], V. Kartvelishvili[93], A.N. Karyukhin[38], E. Kasimi[158], J. Katzy[48], S. Kaur[35], K. Kawade[146], M.P. Kawale[123], C. Kawamoto[89], T. Kawamoto[62], E.F. Kay[37], F.I. Kaya[164], S. Kazakos[109], V.F. Kazanin[38], J.M. Keaveney[34a], R. Keeler[171], G.V. Kehris[61], J.S. Keller[35], J.J. Kempster[152], O. Kepka[134], J. Kerr[162b], B.P. Kerridge[137], B.P. Kerševan[95], L. Keszeghova[29a], R.A. Khan[132], A. Khanov[124], A.G. Kharlamov[38], T. Kharlamova[38], E.E. Khoda[142], M. Kholodenko[133a], T.J. Khoo[19], G. Khoriauli[172], Y. Khoulaki[36a], J. Khubua[155b,*], Y.A.R. Khwaira[130], B. Kibirige[34h], D. Kim[6], D.W. Kim[47a,47b], Y.K. Kim[40], N. Kimura[98], M.K. Kingston[55], A. Kirchhoff[55], C. Kirfel[25], F. Kirfel[25], J. Kirk[137], A.E. Kiryunin[112], S. Kita[163], O. Kivernyk[25], M. Klassen[164], C. Klein[35], L. Klein[172], M.H. Klein[45], S.B. Klein[56], U. Klein[94], A. Klimentov[30], T. Klioutchnikova[37], P. Kluit[117], S. Kluth[112], E. Kneringer[79], T.M. Knight[161], A. Knue[49], M. Kobel[50], D. Kobylianskii[175], S.F. Koch[129], M. Kocian[149], P. Kodyš[136], D.M. Koeck[126], T. Koffas[35], O. Kolay[50], I. Koletsou[4], T. Komarek[87], K. Köneke[55], A.X.Y. Kong[1], T. Kono[121], N. Konstantinidis[98], P. Kontaxakis[56], B. Konya[100], R. Kopeliansky[42], S. Koperny[86a], K. Korcyl[87], K. Kordas[158,d], A. Korn[98], S. Korn[55], I. Korolkov[13], N. Korotkova[38], B. Kortman[117], O. Kortner[112], S. Kortner[112], W.H. Kostecka[118], M. Kostov[29a], V.V. Kostyukhin[147], A. Kotsokechagia[37], A. Kotwal[51],

JHEP10(2025)054

A. Koulouris[37], A. Kourkoumeli-Charalampidi[73a,73b], C. Kourkoumelis[9], E. Kourlitis[112], O. Kovanda[126], R. Kowalewski[171], W. Kozanecki[126], A.S. Kozhin[38], V.A. Kramarenko[38], G. Kramberger[95], P. Kramer[25], M.W. Krasny[130], A. Krasznahorkay[105], A.C. Kraus[118], J.W. Kraus[177], J.A. Kremer[48], N.B. Krengel[147], T. Kresse[50], L. Kretschmann[177], J. Kretzschmar[94], K. Kreul[19], P. Krieger[161], K. Krizka[21], K. Kroeninger[49], H. Kroha[112], J. Kroll[134], J. Kroll[131], K.S. Krowpman[109], U. Kruchonak[39], H. Krüger[25], N. Krumnack[81], M.C. Kruse[51], O. Kuchinskaia[39], S. Kuday[3a], S. Kuehn[37], R. Kuesters[54], T. Kuhl[48], V. Kukhtin[39], Y. Kulchitsky[39], S. Kuleshov[140d,140b], J. Kull[1], E.V. Kumar[111], M. Kumar[34h], N. Kumari[48], P. Kumari[162b], A. Kupco[134], T. Kupfer[49], A. Kupich[38], O. Kuprash[54], H. Kurashige[85], L.L. Kurchaninov[162a], O. Kurdysh[4], Y.A. Kurochkin[38], A. Kurova[38], M. Kuze[141], A.K. Kvam[105], J. Kvita[125], N.G. Kyriacou[108], C. Lacasta[169], F. Lacava[75a,75b], H. Lacker[19], D. Lacour[130], N.N. Lad[98], E. Ladygin[39], A. Lafarge[41], B. Laforge[130], T. Lagouri[178], F.Z. Lahbabi[36a], S. Lai[55], J.E. Lambert[171], S. Lammers[68], W. Lampl[7], C. Lampoudis[158,d], G. Lamprinoudis[102], A.N. Lancaster[118], E. Lançon[30], U. Landgraf[54], M.P.J. Landon[96], V.S. Lang[54], O.K.B. Langrekken[128], A.J. Lankford[165], F. Lanni[37], K. Lantzsch[25], A. Lanza[73a], M. Lanzac Berrocal[169], J.F. Laporte[138], T. Lari[71a], D. Larsen[17], L. Larson[11], F. Lasagni Manghi[24b], M. Lassnig[37], S.D. Lawlor[145], R. Lazaridou[173], M. Lazzaroni[71a,71b], H.D.M. Le[109], E.M. Le Boulicaut[178], L.T. Le Pottier[18a], B. Leban[24b,24a], F. Ledroit-Guillon[60], T.F. Lee[162b], L.L. Leeuw[34c], M. Lefebvre[171], C. Leggett[18a], G. Lehmann Miotto[37], M. Leigh[56], W.A. Leight[105], W. Leinonen[116], A. Leisos[158,v], M.A.L. Leite[83c], C.E. Leitgeb[19], R. Leitner[136], K.J.C. Leney[45], T. Lenz[25], S. Leone[74a], C. Leonidopoulos[52], A. Leopold[150], J.H. Lepage Bourbonnais[35], R. Les[109], C.G. Lester[33], M. Levchenko[38], J. Levêque[4], L.J. Levinson[175], G. Levrini[24b,24a], M.P. Lewicki[87], C. Lewis[142], D.J. Lewis[4], L. Lewitt[145], A. Li[30], B. Li[143a], C. Li[108], C-Q. Li[112], H. Li[143a], H. Li[103], H. Li[15], H. Li[62], H. Li[143a], J. Li[144a], K. Li[14], L. Li[144a], R. Li[178], S. Li[14,114c], S. Li[144b,144a], T. Li[5], X. Li[106], Z. Li[159], Z. Li[14,114c], Z. Li[62], S. Liang[14,114c], Z. Liang[14], M. Liberatore[138], B. Liberti[76a], K. Lie[64c], J. Lieber Marin[83e], H. Lien[68], H. Lin[108], S.F. Lin[151], L. Linden[111], R.E. Lindley[7], J.H. Lindon[37], J. Ling[61], E. Lipeles[131], A. Lipniacka[17], A. Lister[170], J.D. Little[68], B. Liu[14], B.X. Liu[114b], D. Liu[144b,144a], D. Liu[139], E.H.L. Liu[21], J.K.K. Liu[120], K. Liu[144b], K. Liu[144b,144a], M. Liu[62], M.Y. Liu[62], P. Liu[14], Q. Liu[144b,142,144a], X. Liu[62], X. Liu[143a], Y. Liu[114b,114c], Y.L. Liu[143a], Y.W. Liu[62], Z. Liu[66,l], S.L. Lloyd[96], E.M. Lobodzinska[48], P. Loch[7], E. Lodhi[161], T. Lohse[19], K. Lohwasser[145], E. Loiacono[48], J.D. Lomas[21], J.D. Long[42], I. Longarini[165], R. Longo[168], A. Lopez Solis[13], N.A. Lopez-canelas[7], N. Lorenzo Martinez[4], A.M. Lory[111], M. Losada[119a], G. Löschcke Centeno[152], X. Lou[47a,47b], X. Lou[14,114c], A. Lounis[66], P.A. Love[93], M. Lu[66], S. Lu[131], Y.J. Lu[154], H.J. Lubatti[142], C. Luci[75a,75b], F.L. Lucio Alves[114a], F. Luehring[68], B.S. Lunday[131], O. Lundberg[150], J. Lunde[37], N.A. Luongo[6], M.S. Lutz[37], A.B. Lux[26], D. Lynn[30], R. Lysak[134], V. Lysenko[135], E. Lytken[100], V. Lyubushkin[39], T. Lyubushkina[39], M.M. Lyukova[151], M.Firdaus M. Soberi[52], H. Ma[30], K. Ma[62], L.L. Ma[143a], W. Ma[62], Y. Ma[124], J.C. MacDonald[102], P.C. Machado De Abreu Farias[83e], R. Madar[41], T. Madula[98], J. Maeda[85], T. Maeno[30], P.T. Mafa[34c,k], H. Maguire[145], V. Maiboroda[66],

A. Maio[133a,133b,133d], K. Maj[86a], O. Majersky[48], S. Majewski[126], R. Makhmanazarov[38], N. Makovec[66], V. Maksimovic[16], B. Malaescu[130], J. Malamant[128], Pa. Malecki[87], V.P. Maleev[38], F. Malek[60,p], M. Mali[95], D. Malito[97], U. Mallik[80,*], A. Maloizel[5], S. Maltezos[10], A. Malvezzi Lopes[83d], S. Malyukov[39], J. Mamuzic[13], G. Mancini[53], M.N. Mancini[27], G. Manco[73a,73b], J.P. Mandalia[96], S.S. Mandarry[152], I. Mandić[95], L. Manhaes de Andrade Filho[83a], I.M. Maniatis[175], J. Manjarres Ramos[91], D.C. Mankad[175], A. Mann[111], T. Manoussos[37], M.N. Mantinan[40], S. Manzoni[37], L. Mao[144a], X. Mapekula[34c], A. Marantis[158], R.R. Marcelo Gregorio[96], G. Marchiori[5], M. Marcisovsky[134], C. Marcon[71a], E. Maricic[16], M. Marinescu[48], S. Marium[48], M. Marjanovic[123], A. Markhoos[54], M. Markovitch[66], M.K. Maroun[105], G.T. Marsden[103], E.J. Marshall[93], Z. Marshall[18a], S. Marti-Garcia[169], J. Martin[98], T.A. Martin[137], V.J. Martin[52], B. Martin dit Latour[17], L. Martinelli[75a,75b], M. Martinez[13,y], P. Martinez Agullo[169], V.I. Martinez Outschoorn[105], P. Martinez Suarez[13], S. Martin-Haugh[137], G. Martinovicova[136], V.S. Martoiu[28b], A.C. Martyniuk[98], A. Marzin[37], D. Mascione[78a,78b], L. Masetti[102], J. Masik[103], A.L. Maslennikov[39], S.L. Mason[42], P. Massarotti[72a,72b], P. Mastrandrea[74a,74b], A. Mastroberardino[44b,44a], T. Masubuchi[127], T.T. Mathew[126], J. Matousek[136], D.M. Mattern[49], J. Maurer[28b], T. Maurin[59], A.J. Maury[66], B. Maček[95], C. Mavungu Tsava[104], D.A. Maximov[38], A.E. May[103], E. Mayer[41], R. Mazini[34h], I. Maznas[118], S.M. Mazza[139], E. Mazzeo[37], J.P. Mc Gowan[171], S.P. Mc Kee[108], C.A. Mc Lean[6], C.C. McCracken[170], E.F. McDonald[107], A.E. McDougall[117], L.F. Mcelhinney[93], J.A. Mcfayden[152], R.P. McGovern[131], R.P. Mckenzie[34h], T.C. Mclachlan[48], D.J. Mclaughlin[98], S.J. McMahon[137], C.M. Mcpartland[94], R.A. McPherson[171,ac], S. Mehlhase[111], A. Mehta[94], D. Melini[169], B.R. Mellado Garcia[34h], A.H. Melo[55], F. Meloni[48], A.M. Mendes Jacques Da Costa[103], L. Meng[93], S. Menke[112], M. Mentink[37], E. Meoni[44b,44a], G. Mercado[118], S. Merianos[158], C. Merlassino[69a,69c], C. Meroni[71a,71b], J. Metcalfe[6], A.S. Mete[6], E. Meuser[102], C. Meyer[68], J-P. Meyer[138], Y. Miao[114a], R.P. Middleton[137], M. Mihovilovic[66], L. Mijović[52], G. Mikenberg[175], M. Mikestikova[134], M. Mikuž[95], H. Mildner[102], A. Milic[37], D.W. Miller[40], E.H. Miller[149], L.S. Miller[35], A. Milov[175], D.A. Milstead[47a,47b], T. Min[114a], A.A. Minaenko[38], I.A. Minashvili[155b], A.I. Mincer[120], B. Mindur[86a], M. Mineev[39], Y. Mino[89], L.M. Mir[13], M. Miralles Lopez[59], M. Mironova[18a], M.C. Missio[116], A. Mitra[173], V.A. Mitsou[169], Y. Mitsumori[113], O. Miu[161], P.S. Miyagawa[96], T. Mkrtchyan[63a], M. Mlinarevic[98], T. Mlinarevic[98], M. Mlynarikova[37], S. Mobius[20], M.H. Mohamed Farook[115], S. Mohapatra[42], S. Mohiuddin[124], G. Mokgatitswane[34h], L. Moleri[175], U. Molinatti[129], L.G. Mollier[20], B. Mondal[134], S. Mondal[135], K. Mönig[48], E. Monnier[104], L. Monsonis Romero[169], J. Montejo Berlingen[13], A. Montella[47a,47b], M. Montella[122], F. Montereali[77a,77b], F. Monticelli[92], S. Monzani[69a,69c], A. Morancho Tarda[43], N. Morange[66], A.L. Moreira De Carvalho[48], M. Moreno Llácer[169], C. Moreno Martinez[56], J.M. Moreno Perez[23b], P. Morettini[57b], S. Morgenstern[37], M. Morii[61], M. Morinaga[159], M. Moritsu[90], F. Morodei[75a,75b], P. Moschovakos[37], B. Moser[54], M. Mosidze[155b], T. Moskalets[45], P. Moskvitina[116], J. Moss[32], P. Moszkowicz[86a], A. Moussa[36d], Y. Moyal[175], H. Moyano Gomez[13], E.J.W. Moyse[105], O. Mtintsilana[34h], S. Muanza[104],

M. Mucha[25], J. Mueller[132], R. Müller[37], G.A. Mullier[167], A.J. Mullin[33], J.J. Mullin[51], A.C. Mullins[45], A.E. Mulski[61], D.P. Mungo[161], D. Munoz Perez[169], F.J. Munoz Sanchez[103], W.J. Murray[173,137], M. Muškinja[95], C. Mwewa[48], A.G. Myagkov[38,a], A.J. Myers[8], G. Myers[108], M. Myska[135], B.P. Nachman[18a], K. Nagai[129], K. Nagano[84], R. Nagasaka[159], J.L. Nagle[30,ak], E. Nagy[104], A.M. Nairz[37], Y. Nakahama[84], K. Nakamura[84], K. Nakkalil[5], A. Nandi[63b], H. Nanjo[127], E.A. Narayanan[45], Y. Narukawa[159], I. Naryshkin[38], L. Nasella[71a,71b], S. Nasri[119b], C. Nass[25], G. Navarro[23a], J. Navarro-Gonzalez[169], A. Nayaz[19], P.Y. Nechaeva[38], S. Nechaeva[24b,24a], F. Nechansky[134], L. Nedic[129], T.J. Neep[21], A. Negri[73a,73b], M. Negrini[24b], C. Nellist[117], C. Nelson[106], K. Nelson[108], S. Nemecek[134], M. Nessi[37,h], M.S. Neubauer[168], J. Newell[94], P.R. Newman[21], Y.W.Y. Ng[168], B. Ngair[119a], H.D.N. Nguyen[110], J.D. Nichols[123], R.B. Nickerson[129], R. Nicolaidou[138], J. Nielsen[139], M. Niemeyer[55], J. Niermann[37], N. Nikiforou[37], V. Nikolaenko[38,a], I. Nikolic-Audit[130], P. Nilsson[30], I. Ninca[48], G. Ninio[157], A. Nisati[75a], N. Nishu[2], R. Nisius[112], N. Nitika[69a,69c], J-E. Nitschke[50], E.K. Nkadimeng[34b], T. Nobe[159], T. Nommensen[153], M.B. Norfolk[145], B.J. Norman[35], M. Noury[36a], J. Novak[95], T. Novak[95], R. Novotny[135], L. Nozka[125], K. Ntekas[165], N.M.J. Nunes De Moura Junior[83b], J. Ocariz[130], A. Ochi[85], I. Ochoa[133a], S. Oerdek[48,z], J.T. Offermann[40], A. Ogrodnik[136], A. Oh[103], C.C. Ohm[150], H. Oide[84], M.L. Ojeda[37], Y. Okumura[159], L.F. Oleiro Seabra[133a], I. Oleksiyuk[56], G. Oliveira Correa[13], D. Oliveira Damazio[30], J.L. Oliver[165], R. Omar[68], Ö.O. Öncel[54], A.P. O'Neill[20], A. Onofre[133a,133e,e], P.U.E. Onyisi[11], M.J. Oreglia[40], D. Orestano[77a,77b], R. Orlandini[77a,77b], R.S. Orr[161], L.M. Osojnak[131], Y. Osumi[113], G. Otero y Garzon[31], H. Otono[90], G.J. Ottino[18a], M. Ouchrif[36d], F. Ould-Saada[128], T. Ovsiannikova[142], M. Owen[59], R.E. Owen[137], V.E. Ozcan[22a], F. Ozturk[87], N. Ozturk[8], S. Ozturk[82], H.A. Pacey[129], K. Pachal[162a], A. Pacheco Pages[13], C. Padilla Aranda[13], G. Padovano[75a,75b], S. Pagan Griso[18a], G. Palacino[68], A. Palazzo[70a,70b], J. Pampel[25], J. Pan[178], T. Pan[64a], D.K. Panchal[11], C.E. Pandini[60], J.G. Panduro Vazquez[137], H.D. Pandya[1], H. Pang[138], P. Pani[48], G. Panizzo[69a,69c], L. Panwar[130], L. Paolozzi[56], S. Parajuli[168], A. Paramonov[6], C. Paraskevopoulos[53], D. Paredes Hernandez[64b], A. Pareti[73a,73b], K.R. Park[42], T.H. Park[112], F. Parodi[57b,57a], J.A. Parsons[42], U. Parzefall[54], B. Pascual Dias[41], L. Pascual Dominguez[101], E. Pasqualucci[75a], S. Passaggio[57b], F. Pastore[97], P. Patel[87], U.M. Patel[51], J.R. Pater[103], T. Pauly[37], F. Pauwels[136], C.I. Pazos[164], M. Pedersen[128], R. Pedro[133a], S.V. Peleganchuk[38], O. Penc[37], E.A. Pender[52], S. Peng[15], G.D. Penn[178], K.E. Penski[111], M. Penzin[38], B.S. Peralva[83d], A.P. Pereira Peixoto[142], L. Pereira Sanchez[149], D.V. Perepelitsa[30,ak], G. Perera[105], E. Perez Codina[37], M. Perganti[10], H. Pernegger[37], S. Perrella[75a,75b], O. Perrin[41], K. Peters[48], R.F.Y. Peters[103], B.A. Petersen[37], T.C. Petersen[43], E. Petit[104], V. Petousis[135], A.R. Petri[71a,71b], C. Petridou[158,d], T. Petru[136], A. Petrukhin[147], M. Pettee[18a], A. Petukhov[82], K. Petukhova[37], R. Pezoa[140g], L. Pezzotti[24b,24a], G. Pezzullo[178], L. Pfaffenbichler[37], A.J. Pfleger[37], T.M. Pham[176], T. Pham[107], P.W. Phillips[137], G. Piacquadio[151], E. Pianori[18a], F. Piazza[126], R. Piegaia[31], D. Pietreanu[28b], A.D. Pilkington[103], M. Pinamonti[69a,69c], J.L. Pinfold[2], B.C. Pinheiro Pereira[133a], J. Pinol Bel[13], A.E. Pinto Pinoargote[130], L. Pintucci[69a,69c],

JHEP10(2025)054

K.M. Piper[152], A. Pirttikoski[56], D.A. Pizzi[35], L. Pizzimento[64b], A. Plebani[33], M.-A. Pleier[30], V. Pleskot[136], E. Plotnikova[39], G. Poddar[96], R. Poettgen[100], L. Poggioli[130], S. Polacek[136], G. Polesello[73a], A. Poley[148], A. Polini[24b], C.S. Pollard[173], Z.B. Pollock[122], E. Pompa Pacchi[123], N.I. Pond[98], D. Ponomarenko[68], L. Pontecorvo[37], S. Popa[28a], G.A. Popeneciu[28d], A. Poreba[37], D.M. Portillo Quintero[162a], S. Pospisil[135], M.A. Postill[145], P. Postolache[28c], K. Potamianos[173], P.A. Potepa[86a], I.N. Potrap[39], C.J. Potter[33], H. Potti[153], J. Poveda[169], M.E. Pozo Astigarraga[37], R. Pozzi[37], A. Prades Ibanez[76a,76b], J. Pretel[171], D. Price[103], M. Primavera[70a], L. Primomo[69a,69c], M.A. Principe Martin[101], R. Privara[125], T. Procter[86b], M.L. Proffitt[142], N. Proklova[131], K. Prokofiev[64c], G. Proto[112], J. Proudfoot[6], M. Przybycien[86a], W.W. Przygoda[86b], A. Psallidas[46], J.E. Puddefoot[145], D. Pudzha[53], D. Pyatiizbyantseva[116], J. Qian[108], R. Qian[109], D. Qichen[103], Y. Qin[13], T. Qiu[52], A. Quadt[55], M. Queitsch-Maitland[103], G. Quetant[56], R.P. Quinn[170], G. Rabanal Bolanos[61], D. Rafanoharana[112], F. Raffaeli[76a,76b], F. Ragusa[71a,71b], J.L. Rainbolt[40], J.A. Raine[56], S. Rajagopalan[30], E. Ramakoti[39], L. Rambelli[57b,57a], I.A. Ramirez-Berend[35], K. Ran[48,114c], D.S. Rankin[131], N.P. Rapheeha[34h], H. Rasheed[28b], D.F. Rassloff[63a], A. Rastogi[18a], S. Rave[102], S. Ravera[57b,57a], B. Ravina[37], I. Ravinovich[175], M. Raymond[37], A.L. Read[128], N.P. Readioff[145], D.M. Rebuzzi[73a,73b], A.S. Reed[112], K. Reeves[27], J.A. Reidelsturz[177], D. Reikher[126], A. Rej[49], C. Rembser[37], H. Ren[62], M. Renda[28b], F. Renner[48], A.G. Rennie[59], A.L. Rescia[48], S. Resconi[71a], M. Ressegotti[57b,57a], S. Rettie[37], W.F. Rettie[35], M.M. Revering[33], E. Reynolds[18a], O.L. Rezanova[39], P. Reznicek[136], H. Riani[36d], N. Ribaric[51], E. Ricci[78a,78b], R. Richter[112], S. Richter[47a,47b], E. Richter-Was[86b], M. Ridel[130], S. Ridouani[36d], P. Rieck[120], P. Riedler[37], E.M. Riefel[47a,47b], J.O. Rieger[117], M. Rijssenbeek[151], M. Rimoldi[37], L. Rinaldi[24b,24a], P. Rincke[167,55], G. Ripellino[167], I. Riu[13], J.C. Rivera Vergara[171], F. Rizatdinova[124], E. Rizvi[96], B.R. Roberts[18a], S.S. Roberts[139], D. Robinson[33], M. Robles Manzano[102], A. Robson[59], A. Rocchi[76a,76b], C. Roda[74a,74b], S. Rodriguez Bosca[37], Y. Rodriguez Garcia[23a], A.M. Rodríguez Vera[118], S. Roe[37], J.T. Roemer[37], O. Røhne[128], R.A. Rojas[37], C.P.A. Roland[130], A. Romaniouk[79], E. Romano[73a,73b], M. Romano[24b], A.C. Romero Hernandez[168], N. Rompotis[94], L. Roos[130], S. Rosati[75a], B.J. Rosser[40], E. Rossi[129], E. Rossi[72a,72b], L.P. Rossi[61], L. Rossini[54], R. Rosten[122], M. Rotaru[28b], B. Rottler[54], D. Rousseau[66], D. Rousso[48], S. Roy-Garand[161], A. Rozanov[104], Z.M.A. Rozario[59], Y. Rozen[156], A. Rubio Jimenez[169], V.H. Ruelas Rivera[19], T.A. Ruggeri[1], A. Ruggiero[129], A. Ruiz-Martinez[169], A. Rummler[37], Z. Rurikova[54], N.A. Rusakovich[39], H.L. Russell[171], G. Russo[75a,75b], J.P. Rutherfoord[7], S. Rutherford Colmenares[33], M. Rybar[136], P. Rybczynski[86a], A. Ryzhov[45], J.A. Sabater Iglesias[56], H.F-W. Sadrozinski[139], F. Safai Tehrani[75a], S. Saha[1], M. Sahinsoy[82], B. Sahoo[175], A. Saibel[169], B.T. Saifuddin[123], M. Saimpert[138], G.T. Saito[83c], M. Saito[159], T. Saito[159], A. Sala[71a,71b], A. Salnikov[149], J. Salt[169], A. Salvador Salas[157], F. Salvatore[152], A. Salzburger[37], D. Sammel[54], E. Sampson[93], D. Sampsonidis[158,d], D. Sampsonidou[126], J. Sánchez[169], V. Sanchez Sebastian[169], H. Sandaker[128], C.O. Sander[48], J.A. Sandesara[176], M. Sandhoff[177], C. Sandoval[23b], L. Sanfilippo[63a], D.P.C. Sankey[137], T. Sano[89], A. Sansoni[53], L. Santi[37], C. Santoni[41], H. Santos[133a,133b], A. Santra[175],

JHEP10(2025)054

E. Sanzani[24b,24a], K.A. Saoucha[88b], J.G. Saraiva[133a,133d], J. Sardain[7], O. Sasaki[84], K. Sato[163], C. Sauer[37], E. Sauvan[4], P. Savard[161,ai], R. Sawada[159], C. Sawyer[137], L. Sawyer[99], C. Sbarra[24b], A. Sbrizzi[24b,24a], T. Scanlon[98], J. Schaarschmidt[142], U. Schäfer[102], A.C. Schaffer[66,45], D. Schaile[111], R.D. Schamberger[151], C. Scharf[19], M.M. Schefer[20], V.A. Schegelsky[38], D. Scheirich[136], M. Schernau[140f], C. Scheulen[56], C. Schiavi[57b,57a], M. Schioppa[44b,44a], B. Schlag[149], S. Schlenker[37], J. Schmeing[177], E. Schmidt[112], M.A. Schmidt[177], K. Schmieden[102], C. Schmitt[102], N. Schmitt[102], S. Schmitt[48], N.A. Schneider[111], L. Schoeffel[138], A. Schoening[63b], P.G. Scholer[35], E. Schopf[147], M. Schott[25], S. Schramm[56], T. Schroer[56], H-C. Schultz-Coulon[63a], M. Schumacher[54], B.A. Schumm[139], Ph. Schune[138], H.R. Schwartz[139], A. Schwartzman[149], T.A. Schwarz[108], Ph. Schwemling[138], R. Schwienhorst[109], F.G. Sciacca[20], A. Sciandra[30], G. Sciolla[27], F. Scuri[74a], C.D. Sebastiani[37], K. Sedlaczek[118], S.C. Seidel[115], A. Seiden[139], B.D. Seidlitz[42], C. Seitz[48], J.M. Seixas[83b], G. Sekhniaidze[72a], L. Selem[60], N. Semprini-Cesari[24b,24a], A. Semushin[179], D. Sengupta[56], V. Senthilkumar[169], L. Serin[66], M. Sessa[72a,72b], H. Severini[123], F. Sforza[57b,57a], A. Sfyrla[56], Q. Sha[14], E. Shabalina[55], H. Shaddix[118], A.H. Shah[33], R. Shaheen[150], J.D. Shahinian[131], M. Shamim[37], L.Y. Shan[14], M. Shapiro[18a], A. Sharma[37], A.S. Sharma[170], P. Sharma[30], P.B. Shatalov[38], K. Shaw[152], S.M. Shaw[103], Q. Shen[144a], D.J. Sheppard[148], P. Sherwood[98], L. Shi[98], X. Shi[14], S. Shimizu[84], C.O. Shimmin[178], I.P.J. Shipsey[129,*], S. Shirabe[90], M. Shiyakova[39,aa], M.J. Shochet[40], D.R. Shope[128], B. Shrestha[123], S. Shrestha[122,am], I. Shreyber[39], M.J. Shroff[171], P. Sicho[134], A.M. Sickles[168], E. Sideras Haddad[34h,166], A.C. Sidley[117], A. Sidoti[24b], F. Siegert[50], Dj. Sijacki[16], F. Sili[92], J.M. Silva[52], I. Silva Ferreira[83b], M.V. Silva Oliveira[30], S.B. Silverstein[47a], S. Simion[66], R. Simoniello[37], E.L. Simpson[103], H. Simpson[152], L.R. Simpson[6], S. Simsek[82], S. Sindhu[55], P. Sinervo[161], S.N. Singh[27], S. Singh[30], S. Sinha[48], S. Sinha[103], M. Sioli[24b,24a], K. Sioulas[9], I. Siral[37], E. Sitnikova[48], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[21], P. Skubic[123], M. Slawinska[87], I. Slazyk[17], I. Sliusar[128], V. Smakhtin[175], B.H. Smart[137], S.Yu. Smirnov[140b], Y. Smirnov[82], L.N. Smirnova[38,a], O. Smirnova[100], A.C. Smith[42], D.R. Smith[165], J.L. Smith[103], M.B. Smith[35], R. Smith[149], H. Smitmanns[102], M. Smizanska[93], K. Smolek[135], P. Smolyanskiy[135], A.A. Snesarev[39], H.L. Snoek[117], S. Snyder[30], R. Sobie[171,ac], A. Soffer[157], C.A. Solans Sanchez[37], E.Yu. Soldatov[39], U. Soldevila[169], A.A. Solodkov[34h], S. Solomon[27], A. Soloshenko[39], K. Solovieva[54], O.V. Solovyanov[41], P. Sommer[50], A. Sonay[13], A. Sopczak[135], A.L. Sopio[52], F. Sopkova[29b], J.D. Sorenson[115], I.R. Sotarriva Alvarez[141], V. Sothilingam[63a], O.J. Soto Sandoval[140c,140b], S. Sottocornola[68], R. Soualah[88a], Z. Soumaimi[36e], D. South[48], N. Soybelman[175], S. Spagnolo[70a,70b], M. Spalla[112], D. Sperlich[54], B. Spisso[72a,72b], D.P. Spiteri[59], L. Splendori[104], M. Spousta[136], E.J. Staats[35], R. Stamen[63a], E. Stanecka[87], W. Stanek-Maslouska[48], M.V. Stange[50], B. Stanislaus[18a], M.M. Stanitzki[48], B. Stapf[48], E.A. Starchenko[38], G.H. Stark[139], J. Stark[91], P. Staroba[134], P. Starovoitov[88b], R. Staszewski[87], G. Stavropoulos[46], A. Stefl[37], P. Steinberg[30], B. Stelzer[148,162a], H.J. Stelzer[132], O. Stelzer-Chilton[162a], H. Stenzel[58], T.J. Stevenson[152], G.A. Stewart[37], J.R. Stewart[124], M.C. Stockton[37], G. Stoicea[28b], M. Stolarski[133a], S. Stonjek[112], A. Straessner[50], J. Strandberg[150], S. Strandberg[47a,47b], M. Stratmann[177],

JHEP10(2025)054

M. Strauss[123], T. Strebler[104], P. Strizenec[29b], R. Ströhmer[172], D.M. Strom[126], R. Stroynowski[45], A. Strubig[47a,47b], S.A. Stucci[30], B. Stugu[17], J. Stupak[123], N.A. Styles[48], D. Su[149], S. Su[62], X. Su[62], D. Suchy[29a], K. Sugizaki[131], V.V. Sulin[38], M.J. Sullivan[94], D.M.S. Sultan[129], L. Sultanaliyeva[38], S. Sultansoy[3b], S. Sun[176], W. Sun[14], O. Sunneborn Gudnadottir[167], N. Sur[100], M.R. Sutton[152], H. Suzuki[163], M. Svatos[134], P.N. Swallow[33], M. Swiatlowski[162a], T. Swirski[172], A. Swoboda[37], I. Sykora[29a], M. Sykora[136], T. Sykora[136], D. Ta[102], K. Tackmann[48,z], A. Taffard[165], R. Tafirout[162a], Y. Takubo[84], M. Talby[104], A.A. Talyshev[38], K.C. Tam[64b], N.M. Tamir[157], A. Tanaka[159], J. Tanaka[159], R. Tanaka[66], M. Tanasini[151], Z. Tao[170], S. Tapia Araya[140g], S. Tapprogge[102], A. Tarek Abouelfadl Mohamed[109], S. Tarem[156], K. Tariq[14], G. Tarna[28b], G.F. Tartarelli[71a], M.J. Tartarin[91], P. Tas[136], M. Tasevsky[134], E. Tassi[44b,44a], A.C. Tate[168], G. Tateno[159], Y. Tayalati[36e,ab], G.N. Taylor[107], W. Taylor[162b], A.S. Tegetmeier[91], P. Teixeira-Dias[97], J.J. Teoh[161], K. Terashi[159], J. Terron[101], S. Terzo[13], M. Testa[53], R.J. Teuscher[161,ac], A. Thaler[79], O. Theiner[56], T. Theveneaux-Pelzer[104], D.W. Thomas[97], J.P. Thomas[21], E.A. Thompson[18a], P.D. Thompson[21], E. Thomson[131], R.E. Thornberry[45], C. Tian[62], Y. Tian[56], V. Tikhomirov[82], Yu.A. Tikhonov[39], S. Timoshenko[38], D. Timoshyn[136], E.X.L. Ting[1], P. Tipton[178], A. Tishelman-Charny[30], K. Todome[141], S. Todorova-Nova[136], S. Todt[50], L. Toffolin[69a,69c], M. Togawa[84], J. Tojo[90], S. Tokár[29a], O. Toldaiev[68], G. Tolkachev[104], M. Tomoto[84,113], L. Tompkins[149,o], E. Torrence[126], H. Torres[91], E. Torró Pastor[169], M. Toscani[31], C. Tosciri[40], M. Tost[11], D.R. Tovey[145], T. Trefzger[172], P.M. Tricarico[13], A. Tricoli[30], I.M. Trigger[162a], S. Trincaz-Duvoid[130], D.A. Trischuk[27], A. Tropina[39], L. Truong[34c], M. Trzebinski[87], A. Trzupek[87], F. Tsai[151], M. Tsai[108], A. Tsiamis[158], P.V. Tsiareshka[39], S. Tsigaridas[162a], A. Tsirigotis[158,v], V. Tsiskaridze[161], E.G. Tskhadadze[155a], M. Tsopoulou[158], Y. Tsujikawa[89], I.I. Tsukerman[38], V. Tsulaia[18a], S. Tsuno[84], K. Tsuri[121], D. Tsybychev[151], Y. Tu[64b], A. Tudorache[28b], V. Tudorache[28b], S.B. Tuncay[129], S. Turchikhin[57b,57a], I. Turk Cakir[3a], R. Turra[71a], T. Turtuvshin[39,ad], P.M. Tuts[42], S. Tzamarias[158,d], E. Tzovara[102], Y. Uematsu[84], F. Ukegawa[163], P.A. Ulloa Poblete[140c,140b], E.N. Umaka[30], G. Unal[37], A. Undrus[30], G. Unel[165], J. Urban[29b], P. Urrejola[140a], G. Usai[8], R. Ushioda[160], M. Usman[110], F. Ustuner[52], Z. Uysal[82], V. Vacek[135], B. Vachon[106], T. Vafeiadis[37], A. Vaitkus[98], C. Valderanis[111], E. Valdes Santurio[47a,47b], M. Valente[37], S. Valentinetti[24b,24a], A. Valero[169], E. Valiente Moreno[169], A. Vallier[91], J.A. Valls Ferrer[169], D.R. Van Arneman[117], T.R. Van Daalen[142], A. Van Der Graaf[49], H.Z. Van Der Schyf[34h], P. Van Gemmeren[6], M. Van Rijnbach[37], S. Van Stroud[98], I. Van Vulpen[117], P. Vana[136], M. Vanadia[76a,76b], U.M. Vande Voorde[150], W. Vandelli[37], E.R. Vandewall[124], D. Vannicola[157], L. Vannoli[53], R. Vari[75a], M. Varma[178], E.W. Varnes[7], C. Varni[18b], D. Varouchas[66], L. Varriale[169], K.E. Varvell[153], M.E. Vasile[28b], L. Vaslin[84], M.D. Vassilev[149], A. Vasyukov[39], L.M. Vaughan[124], R. Vavricka[136], T. Vazquez Schroeder[13], J. Veatch[32], V. Vecchio[103], M.J. Veen[105], I. Veliscek[30], I. Velkovska[95], L.M. Veloce[161], F. Veloso[133a,133c], S. Veneziano[75a], A. Ventura[70a,70b], S. Ventura Gonzalez[138], A. Verbytskyi[112], M. Verducci[74a,74b], C. Vergis[96], M. Verissimo De Araujo[83b], W. Verkerke[117], 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. Villhauer[40], E. Vilucchi[53], M. Vincent[169], M.G. Vincter[35], A. Visibile[117], 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. Vujinovic[102], I. Vukotic[40], I.K. Vyas[35], J.F. Wack[33], S. Wada[163], C. Wagner[149], 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 Pass[59], 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. Wenke[112], 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. Williams[131], 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. Wittgen[149], M. Wobisch[99], T. Wojtkowski[60], Z. Wolffs[117], J. Wollrath[37], M.W. Wolter[87], H. Wolters[133a,133c], M.C. Wong[139], E.L. Woodward[42], S.D. Worm[48], B.K. Wosiek[87], K.W. Woźniak[87], S. Wozniewski[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. Yang[62], W-M. Yao[18a], C.L. Yardley[152], J. Ye[14], S. Ye[30], X. Ye[62], Y. Yeh[98], I. Yeletskikh[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. Young[126], 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],

JHEP10(2025)054

J. Zheng[114a], K. Zheng[168], X. Zheng[62], Z. Zheng[149], D. Zhong[168], B. Zhou[108], H. Zhou[7], N. Zhou[144a], Y. Zhou[15], Y. Zhou[114a], Y. Zhou[7], C.G. Zhu[143a], J. Zhu[108], X. Zhu[144b], Y. Zhu[144a], Y. Zhu[62], X. Zhuang[14], K. Zhukov[68], N.I. Zimine[39], J. Zinsser[63b], M. Ziolkowski[147], L. Živković[16], A. Zoccoli[24b,24a], K. Zoch[61], A. Zografos[37], T.G. Zorbas[145], O. Zormpa[46], L. Zwalinski[37]

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JHEP10(2025)054

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JHEP10(2025)054

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JHEP10(2025)054

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JHEP10(2025)054

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JHEP10(2025)054