PROCEEDINGS OF SCIENCE

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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The first measurement of the high-mass $\tau\bar{\tau}$ production cross-section is presented, using 140 fb^{-1} of proton-proton collision data, recorded with the ATLAS detector at $\sqrt{s} = 13$ TeV. The measurement agrees with the predictions of the Standard Model. The same process is also exploited to constrain new physics models affecting the Standard Model flavour sector. A fit to the τ-lepton pair invariant mass distribution is performed as a function of b-jet multiplicity, to constrain the non-resonant production of leptoquark particles and heavy Z' bosons that couple preferentially to third generation leptons, as well as new interactions described by an effective field theory. The constraints on leptoquark particles improve on previous results and exclude models preferred to interpret the flavour anomalies in B-hadron decays. The constraints on effective field theory couplings include those affecting $g-2$ of the τ-lepton.

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1. Introduction

The Drell-Yan production of di-lepton pairs is a prominent process to study particle interactions. At high invariant mass, the Drell-Yan production is sensitive to a variety of new interactions, which make it a probe for new physics. Measurements of anomalous decay rates of B-mesons into $D^{(*)}\tau\nu$ can be explained by the presence of a leptoquark particle or Z' boson that preferentially couples to the third generation of fermions compared to the first two generations. These new interactions would affect the $\tau\bar{\tau}$ production and can be tested through a precise measurement of the process.

This note summarises the first measurement of the inclusive $\tau\bar{\tau}$ fiducial cross-section as a function of the visible invariant mass of the di-lepton pair, as well as a search for leptoquark particles, Z' bosons and new particle states, performed with the ATLAS experiment [1] at the Large Hadron Collider (LHC) and recently published in Ref. [2].

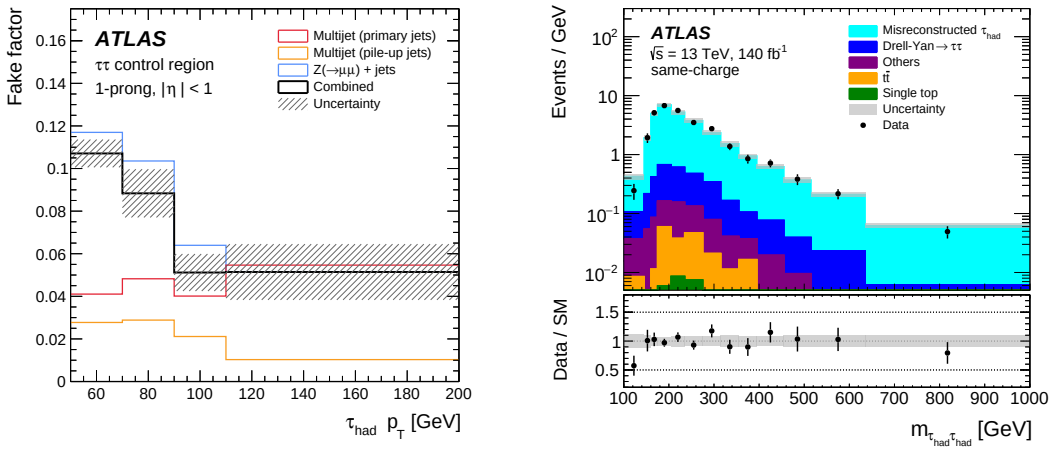
2. Event selection and modelling

The analysis exploits the ATLAS Run 2 proton-proton (pp) collision dataset, recorded in the years 2015-2018 at a centre of mass energy of $\sqrt{s}$ = 13 TeV. The standard ATLAS algorithms are used to reconstruct hadronic τ-lepton decays, jets, electrons and muons, and to tag jets originating from the hadronisation of b-quarks, as detailed in Ref. [2]. Events are primarily collected with a trigger requiring two hadronically decaying τ-leptons (τ_{had}) or one τ-lepton in the event. Exactly two reconstructed hadronically decaying τ-leptons (τ_{had}) are requested in the events. The validation of the modelling is performed using events with one τ_{had} and one charged lepton (e or μ). The data are separated in categories of b-jet multiplicity (0, 1, $\geq$ 2 b-jets in the event).

The data are modelled using Monte Carlo event samples corresponding to the dominant Drell-Yan $\tau\bar{\tau}$ and top-quark production, and a minor contribution from di-boson and Higgs boson production. Details on the Monte Carlo generators used, the PDF set and the set of tuned parameters are provided in Ref. [2]. The analysis selection region includes a sizeable background from jets misreconstructed as fake hadronic τ-leptons (fake τ_{had}). This background is estimated exploiting the Universal Fake Factor method, a novel technique published by ATLAS in Ref. [3]. The method relies primarily on data and exploits a sample enriched in misreconstructed jets to predict the background in the measurement sample. The τ_{had} objects used in the analysis include a requirement that a Recurrent Neural Network (RNN) score [4] is larger than 0.8. A fake factor is defined as the ratio of the event yields where a misreconstructed jet satisfied RNN $>$ 0.8 to those with RNN $<$ 0.8. The fake factor is evaluated as a combination of fake factors measured in samples enriched in different types of jets originating fake τ-leptons (Figure 1(a)). The fake τ-lepton background estimation is validated by observing the agreement between the data and the total background prediction in events with two same-charge τ_{had} (Figure 1(b)) and with one τ_{had} and a same-charge muon or electron.

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

The measured differential cross-section is defined by a kinematic particle level selection that closely reflects the detector-level selection in order to minimise the extrapolation. Detector effects are unfolded using a Bayesian method [5]. The transfer matrix, as well as the reconstruction



(a) (b)

Figure 1: (a) The fake factor as a function of τ_{had} p_{T} (black), for τ_{had} with one associated charged track evaluated and $|\eta| < 1$. The fake factor is evaluated as a combination of fake factors measured in event categories enriched in specific fake τ-lepton sources (colour). (b) The distribution of the visible invariant mass in a region with same-charge τ_{had}, showing agreement between data and the background prediction. Figures from [2].

efficiency and the fiducial fraction are evaluated using the nominal Monte Carlo samples. Two iterations of the unfolding method are used.

The measured cross-section is shown in Figure 2. The data represent inclusive yields of all processes producing two τ_{had} in the final state from pp collisions. The measurement is compared to the Standard Model prediction where the Drell-Yan and top-production are modelled from Sherpa 2.2.11 [6] (MEPS@NLO) and Powheg Box + Pythia 8 [7, 8] (NLOPS) and the other minor backgrounds with nominal generators. The uncertainty bars on the data include all the experimental uncertainties. The uncertainty in the Monte Carlo predictions include the effect of QCD renormalisation and factorisation scale variations, and PDF uncertainties. The unfolded measurement agrees with the Standard Model prediction within the uncertainty.

4. Search for leptoquark particles, Z' bosons and new non-resonant interactions

At high invariant mass the production of $\tau\bar{\tau}$ pairs is sensitive to new interactions preferentially coupling to third generation fermions. Such couplings would modify the $\tau\bar{\tau}$ mass distribution in events with one or two b-jets, as the presence of b-jets in the final state suggests that the primary interaction involves b-quarks.

The analysis constrains vector leptoquarks (U) [9] exchanged in the non-resonant production of $\tau\bar{\tau}$ pairs (t-channel). The relevant Lagrangian term depends on the β_L^{i3} and β_R^{i3} couplings to the left-handed and right-handed fermion states, where the i-index runs over the three fermion generations. The leptoquark diagrams interfere destructively with the Standard Model Drell-Yan production. Scalar leptoquarks $\tilde{S}_1$ [10] are also probed in the study. The relevant Lagrangian term depends on a λ coupling parameter. The analysis additionally probes the Z' boson exchange via $b\bar{b}$

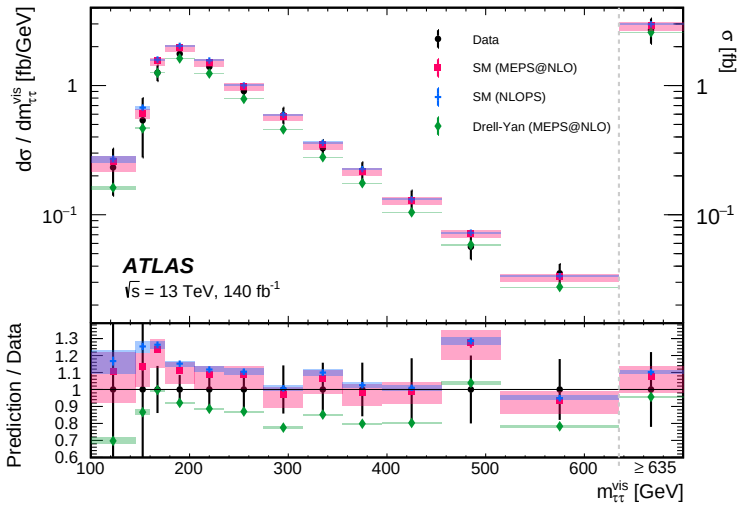


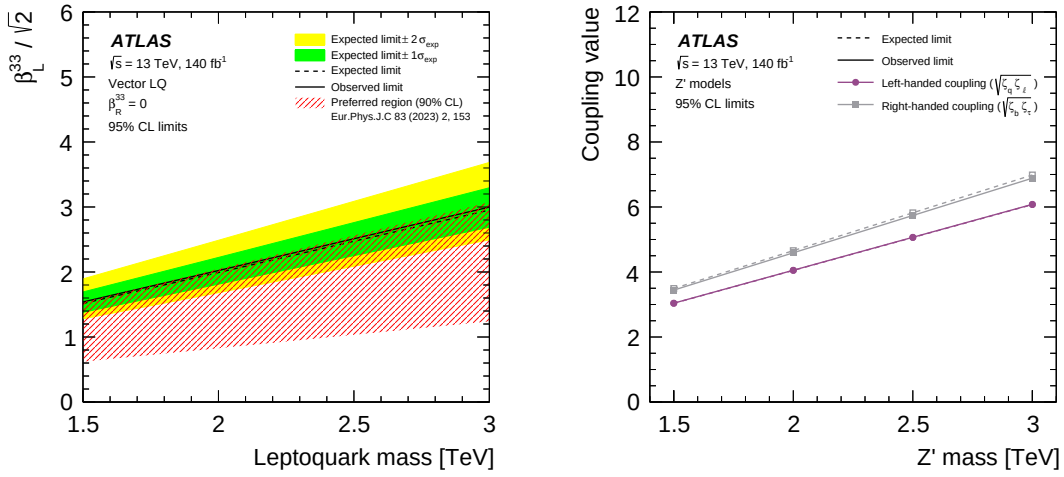
Figure 2: Unfolded fiducial cross-section of the τ-lepton pair production, differential in the visible invariant mass of the τ-lepton pair ($m_{\tau\tau}^{\text{vis}}$). The data are compared to the Standard Model prediction of the SHERPA 2.2.11 (MEPS@NLO) and the POWHEG BOX + PYTHIA 8 (NLOPS) generators. Figure from [2].

annihilation [9]. The relevant Lagrangian term depends on the ζ_q (ζ_ℓ) and ζ_d (ζ_τ) couplings to third generation left-handed and right-handed quark (lepton) states. Both the pure beyond Standard Model (BSM) and the interference signal contributions are considered in the analysis. The interference is destructive for the vector leptoquarks and constructive for the scalar leptoquark and the Z' bosons.

A profile likelihood fit to the data is performed using the yields in the three bins of b-jet multiplicity (0, 1 and $\geq$ 2) and three bins of the invariant mass of the $\tau_{\text{had}}\tau_{\text{had}}$ pair (100-250, 250-400, and 400 – 1000 GeV). The parameter of interest in the fit is the square of the coupling of the tested model. Systematic uncertainties are included in the fit as nuisance parameters.

Since no evidence of a leptoquark nor Z' boson signal is observed, limits are set on the model couplings as a function of the particle mass. Limits are derived for four benchmark mass values of 1.5, 2, 2.5 and 3 TeV. The β_L^{33} coupling is constrained in a scenario preferred by B-hadron anomalies. The limit excludes a small portion of the preferred phase-space (Figure 3(a)). Constraints are derived on the scalar leptoquark coupling λ, and on the Z' boson coupling combinations $\sqrt{\zeta_q\zeta_\ell}$ and $\sqrt{\zeta_b\zeta_\tau}$ (Figure 3(b)). The limits improve on previous constraints from ATLAS [11] and on those from CMS [12], and consider the interference term for the first time. The CMS search for leptoquarks observed a local excess of 2.8 standard deviations relative to the background-only model. 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. This analysis excludes these parameter values.

General non-resonant interactions described by an Effective Field Theory (EFT) have additionally been probed, with the same likelihood fit strategy. Four-fermion, Higgs sector and Gauge sector operators relevant to the $pp \to \tau\bar{\tau}$ have been considered. Figure 4 shows the best-fit value and the 68% confidence level intervals, determined from a fit to the interference only signal (linear) and interference + BSM signals (linear + quad.). The $c_{\tau\gamma}$ operator affects the τ-lepton anomalous magnetic moment a_τ [13]. The confidence interval obtained on $c_{\tau\gamma}$ is a about factor of seven smaller than the one derived from the ATLAS measurement of a_τ in lead-lead collisions [14] and



(a) (b)

Figure 3: Coupling limits as a function of the particle mass for: (a) a vector leptoquark coupling to a τ-lepton and a b-quark. (b) a Z' boson coupling to left-handed or right-handed fermions. Figure from [2].

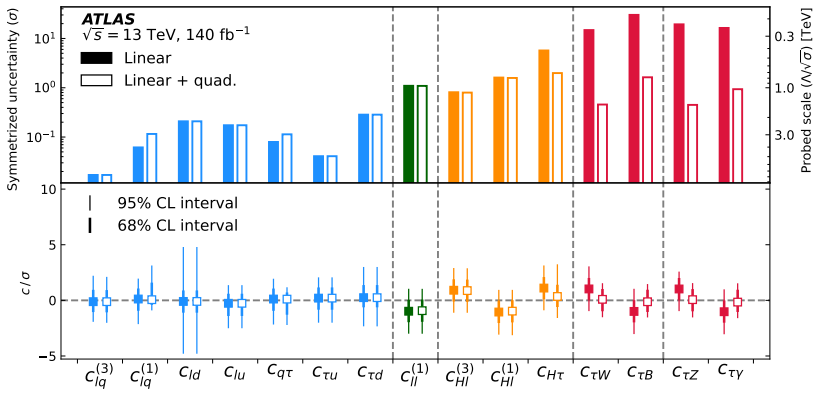


Figure 4: Constraints on the EFT coupling coefficients using fits to the interference-only signal (linear) as well as fits using both the interference and the BSM terms (linear + quad.). The symmetrised 1σ uncertainty is evaluated at assuming a cut-off scale of Λ = 1 TeV. Figure from [2].

competitive with the one from the CMS analysis of $\gamma\gamma \to \tau\bar{\tau}$ events in pp collisions [15].

5. Conclusion

The first unfolded differential measurement of $\tau\bar{\tau}$ production has been performed by ATLAS, using the 140 fb^{-1} Run 2 dataset of pp collisions at $\sqrt{s}$ = 13 TeV. The measurement agrees with the prediction of the Standard Model. A fit to the di-lepton visible invariant mass has been utilised to constrain the non-resonant production of leptoquark particles, Z' bosons and EFT couplings, improving on previous results and constraining models preferred by the B-hadron anomalies.

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