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Improved reconstruction of highly boosted τ-lepton pairs in the $\tau\tau \to (\mu\nu_\mu\nu_\tau)$(hadrons + ν_τ) decay channels with the ATLAS detector

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Abstract This paper presents a new τ-lepton reconstruction and identification procedure at the ATLAS detector at the Large Hadron Collider, which leads to significantly improved performance in the case of physics processes where a highly boosted pair of τ-leptons is produced and one τ-lepton decays into a muon and two neutrinos (τ_μ), and the other decays into hadrons and one neutrino (τ_{had}). By removing the muon information from the signals used for reconstruction and identification of the τ_{had} candidate in the boosted pair, the efficiency is raised to the level expected for an isolated τ_{had}. The new procedure is validated by selecting a sample of highly boosted $Z \to \tau_\mu\tau_{\text{had}}$ candidates from the data sample of 140 fb^{-1} of proton–proton collisions at 13 TeV recorded with the ATLAS detector. Good agreement is found between data and simulation predictions in both the $Z \to \tau_\mu\tau_{\text{had}}$ signal region and in a background validation region. The results presented in this paper demonstrate the effectiveness of the τ_{had} reconstruction with muon removal in enhancing the signal sensitivity of the boosted $\tau_\mu\tau_{\text{had}}$ channel at the ATLAS detector.

Contents

1 Introduction

The τ-lepton is the heaviest known lepton, with a mass of 1.777 GeV, and a lifetime of 2.9×10^{-13} s [1]. It has a 35% probability of decaying leptonically into a lighter lepton and two neutrinos: $\tau \to e\nu_e\nu_\tau$ or $\tau \to \mu\nu_\mu\nu_\tau$ (denoted τ_μ), collectively referred to as τ_{lep}. In the remaining 65% of cases, the τ-lepton decays hadronically (τ_{had}) into one or more charged hadrons and zero or more neutral hadrons, plus one neutrino. Thus, the fraction of τ-lepton pairs resulting in a $\tau_\mu\tau_{\text{had}}$ final state is 23%.

The standard ATLAS τ_{had} reconstruction and identification procedure [2–5] starts with the reconstruction of the visible decay products of a τ_{had} candidate ($\tau_{\text{had-vis}}$), which is seeded by a jet clustered using the anti-k_t algorithm [6,7] with a radius parameter $R = 0.4$.[1] The jet reconstruction algorithm operates on the topological calorimeter cells [8] calibrated to the local hadronic energy scale [9]. This seed

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[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 $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

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jet is referred to as τ_{seed} jet. Only τ_{seed} jets with transverse momentum $p_{\text{T}} > 5$ GeV and pseudorapidity $|\eta| < 2.5$ are considered. Dedicated algorithms [5] are run to identify the production vertex, associating and classifying reconstructed inner detector tracks, and calibrating the energy of the τ_{had} candidate. Tracks that have passed the τ_{seed} jet association requirements are classified into four categories: 'Tau Tracks', 'Conversion Tracks', 'Isolation Tracks' and 'Fake Tracks'. Only 'Tau Tracks' are used to determine the number of charged decay products and thus the charge of the τ lepton. After reconstruction, the τ_{had} candidate is classified by the τ_{had} identification algorithm (TauID), a recurrent neural network (RNN) classifier [4], to determine its likelihood of being the decay product of a τ_{had}. Several working points, 'Tight', 'Medium', 'Loose' and 'VeryLoose', are then defined based on optimised requirements on the RNN score with different τ_{had} identification efficiencies [4].

The standard TauID algorithm is efficient unless activity from other particles is found inside the τ_{seed} jet. One of these cases is when a pair of τ-leptons originates from a highly boosted resonance and the decay products of the two τ-leptons are reconstructed within the radius of a single τ_{seed} jet. The reconstruction and identification of boosted systems in which both τ-leptons decay hadronically is achieved by searching for hadronic τ-like substructure using a boosted decision tree within a large radius seed jet [10]. In this analysis, the decay into the $\tau_\mu \tau_{\text{had}}$ final state is considered.

Muon reconstruction [11] in the ATLAS detector is based on the information from the inner tracking detector (ID) and the muon spectrometer (MS), complemented by calorimeter data. The reconstruction begins by identifying tracks in the MS, followed by matching these with tracks in the ID. In cases where a candidate can be made from ID and MS tracks, a combined fit is performed, taking into account the energy loss in the calorimeters. This study considers muons satisfying the 'Medium' identification working point [11], which ensures a combined muon where the ID track matches the MS signature. The minimum ionising nature of the muon and the fact that the muon reconstruction is independent of its isolation [11] enables the possibility of removing the ID track and clusters produced by the muon from the τ_{seed} jet produced by a boosted $\tau_\mu \tau_{\text{had}}$ system. The kinematic variables that are subsequently supplied to the TauID algorithm are re-calculated without the interference of the muon. The τ_{had} reconstructed with this method is referred to as $\tau_{\text{had}}^{\not\mu}$.

The $\tau_{\text{had}}^{\not\mu}$ method was developed using simulated events corresponding to a beyond the Standard Model (BSM) process with a high-mass graviton [12] decaying into two Higgs bosons as signal. Before using this technique in future BSM searches, it is important to demonstrate its performance using a Standard Model (SM) process. As a validation for the new method, the production of two τ-leptons originating from a highly boosted Z boson giving the final state of interest, $Z \to \tau_\mu \tau_{\text{had}}$, is used.

This paper is organised as follows. The ATLAS detector is described briefly in Sect. 2. The data and simulated samples are described in Sect. 3. The development of the boosted $\tau_{\text{had}}^{\not\mu}$ method is described in Sect. 4. The analysis methods and the results for the $Z \to \tau_\mu \tau_{\text{had}}$ validation are described in Sect. 5. Finally, the conclusions are given in Sect. 6.

2 ATLAS detector

The ATLAS detector [13] at the Large Hadron Collider (LHC) [14] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle. It consists of an ID surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a MS. The inner tracking detector 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 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 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 $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [15] detector, which is located close to the beampipe. A two-level trigger system is used to select events [16]. 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 [17] 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.

3 Data and simulated event samples

3.1 Simulated samples for the development of the method

Monte Carlo (MC) simulated event samples [18] of signal and backgrounds are used to develop the $\tau_{\text{had}}^{\not\mu}$ method and to evaluate the τ_{had} reconstruction and identification efficien-

cies, as well as the background rejection power. The signal samples consist of BSM gravitons [12] decaying into a pair of Higgs bosons, with the hypothetical graviton mass ranging from 1 to 5 TeV. For this study, the SM Higgs bosons are constrained to decay into a pair of τ-leptons. The signal process is referred to as $G \to HH \to 4\tau$.

High-p_{T}, semileptonically decaying heavy-flavour hadrons may produce a detector signature that has some similarities with the signal sample of boosted $\tau_\mu \tau_{\mathrm{had}}$ pairs, since the invariant mass of the charm hadron produced in the semileptonic decay of a bottom hadron is comparable to the τ-lepton mass. The top-antitop-quark process ($t\bar{t}$) is used to model this type of background.

The $G \to HH \to 4\tau$ signal samples were simulated using the MadGraph5_aMC@NLO [19] generator using matrix elements (ME) at leading-order (LO) in quantum chromodynamics (QCD) with the NNPDF2.3lo [20] parton distribution function (PDF) set. The production of $t\bar{t}$ events was modelled using the Powheg Box v2 [21–24] generator at next-to-leading order (NLO) in QCD with the NNPDF3.0nlo [25] PDF set and the h_{damp} parameter[2] set to 1.5 m_{top} [26].

Pythia 8.230 [27] with the A14 [28] set of tuned parameters (tune) and NNPDF2.3lo PDF set was used for the simulation of the parton showering and hadronisation for both the $G \to HH \to 4\tau$ samples and the $t\bar{t}$ samples. The decays of bottom and charm hadrons were performed by EvtGen 1.6.0 [29]. The effect of multiple interactions in the same and neighbouring bunch crossings (pile-up) was modelled by overlaying the original hard-scattering event with simulated inelastic proton–proton collisions generated by Pythia 8.186 [30] with the A3 tune [31] and the MSTW2008lo PDF set [32]. The MC samples were reweighted so that the pile-up distribution matches the one observed in the data. All MC samples were passed through the ATLAS detector simulation based on Geant4 [33].

3.2 Data and simulated samples for the validation of the method

For the $Z \to \tau_\mu \tau_{\mathrm{had}}$ validation analysis, the Run 2 data sample collected in proton–proton collisions at the LHC with $\sqrt{s} = 13$ TeV and a 25 ns bunch crossing interval is used. The integrated luminosity of the sample recorded while all relevant components of the ATLAS detector were operating normally corresponds to 140 fb^{-1} [34,35].

Simulated samples provide predictions for both signal and background processes. As described in Sect. 3.1, the simulation includes the effect of pile-up and the detector response. All MC samples undergo calibrations and corrections to match the performance in data. EvtGen 1.6.0 [29] was used again to decay bottom and charm hadrons. The rest of this section gives details of the specific MC samples used in this study.

The dominant production channel of the boosted $Z \to \tau_\mu \tau_{\mathrm{had}}$ final states, a Z boson produced in association with jets, was modelled using the Sherpa 2.2.14 [36] generator for the $Z \to \tau\tau$ channel, while Sherpa 2.2.11 was used to model $Z \to \ell\ell$ ($\ell = e, \mu$) decays. The ME calculations ranged from NLO in QCD for final states with up to two additional parton emissions to LO in QCD for up to five additional parton emissions. The MEs were merged with the Sherpa parton shower following the MEPS@LO [37] prescription and using the NNPDF3.0nnlo [25] PDF set. The production of W bosons with jets, and the production of WW, WZ, and ZZ boson pairs, were simulated using Sherpa 2.2.11 with configurations similar to those used in the Z+jets sample. Measurements of the distribution of Z-boson transverse momentum (p_{T}^Z) using light-lepton pair events at $\sqrt{s} = 13$ TeV [38] indicate that Sherpa 2.2.11 underestimates the cross-section for $p_{\mathrm{T}}^Z > 100$ GeV by approximately 10% [39]. The simulation of initial-state QCD radiation is expected to be the same in the Sherpa 2.2.14 samples used in this study. A 10% correction is therefore applied to the predicted event yields for $Z \to \tau\tau$ in the validation analysis, with the full size of this correction quoted as a systematic uncertainty.

The production of $t\bar{t}$ events was modelled using the same configuration as the one used for the method development as in Sect. 3.1. Single-top t-channel production was modelled using the Powheg Box v2 [22–24,40] generator at NLO in QCD using the four-flavour scheme and the corresponding NNPDF3.0nlo PDF set. The associated production of top quarks with W bosons (tW) was modelled using the Powheg Box v2 generator at NLO in QCD using the five-flavour scheme and the NNPDF3.0nlo PDF set. The diagram removal scheme [41] was used to remove interference and overlap with $t\bar{t}$ production. In both cases the generated events were interfaced to Pythia 8.230 using the A14 tune and the NNPDF2.3lo PDF set.

The production of Higgs bosons via gluon–gluon fusion and vector–boson fusion was modeled following the configuration detailed in Ref. [42].

[2] The h_{damp} parameter is a resummation damping factor and one of the parameters that controls the matching of Powheg matrix elements to the parton shower and thus effectively regulates the high-transverse-momentum radiation against which the $t\bar{t}$ system recoils.

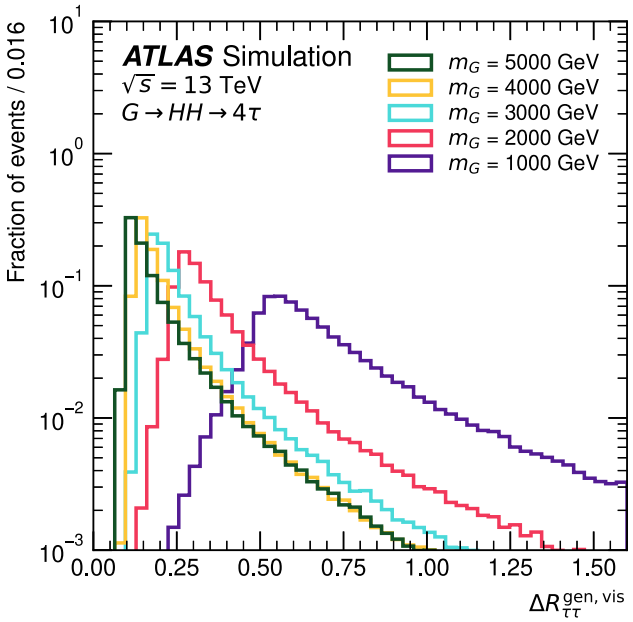


Fig. 1 The distributions of the $\Delta R_{\tau\tau}^{\text{gen,vis}}$ for the generator-level $\tau_\mu\tau_{\text{had}}$ pair in $G \to HH \to 4\tau$ signal events, with graviton masses m_G ranging from 1000 to 5000 GeV

4 Development of the boosted $\tau_{\text{had}}^{\text{bst}}$ reconstruction method

4.1 Muon removal and re-reconstruction of the τ_{had} candidate

The $\tau_{\text{had}}^{\text{bst}}$ method was developed with simulated $G \to HH \to 4\tau$ signal samples with generator-level information used to evaluate the performance of the method. The angular distance at the generator-level between the $\tau_{\text{had-vis}}$ and the muon is measured by $\Delta R_{\tau\tau}^{\text{gen,vis}}$. In Fig. 1, the $\Delta R_{\tau\tau}^{\text{gen,vis}}$ distributions of the $\tau_\mu\tau_{\text{had}}$ pairs in the $G \to HH \to 4\tau$ samples are presented.

For $\Delta R_{\tau\tau}^{\text{gen,vis}} < 0.4$, it is more likely that the muon will be reconstructed inside the τ_{seed} jet.

In this study, MC generator-level information is used to match generated $\tau_\mu\tau_{\text{had}}$ pairs with their reconstructed counterparts. The reconstructed τ_{seed} jet is generator-matched if at least one ID track matches the muon from the τ_{lep} decay or the charged hadron(s) from the τ_{had} decay. Only τ_{seed} jets originating from a boosted $\tau_\mu\tau_{\text{had}}$ pair are considered. Other τ_{seed} jets, such as those associated with QCD jets, are neglected. The MC generator-level visible τ-lepton decay products are required to satisfy the requirements $p_{\text{T}} > 20$ GeV and $|\eta| < 2.5$ to ensure that the τ_{seed} jets are within the tracking acceptance of the ATLAS detector.

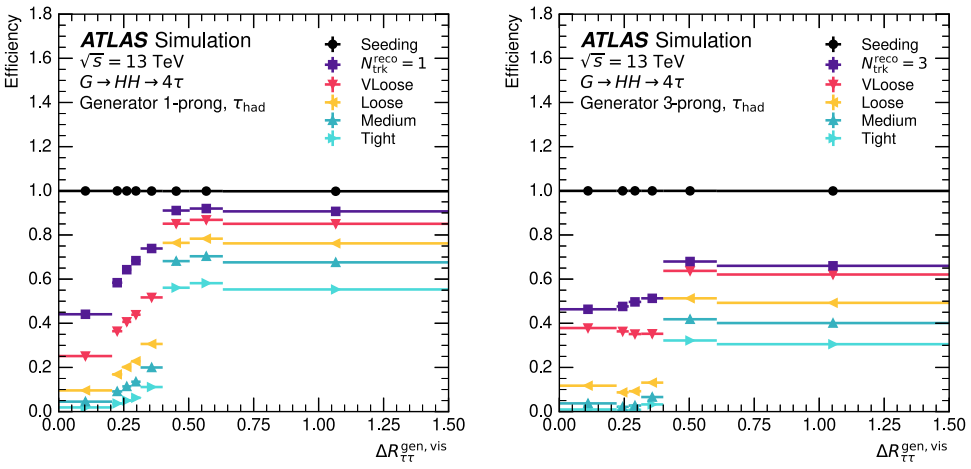
Below the $\Delta R_{\tau\tau}^{\text{gen,vis}} < 0.4$ threshold, the standard τ_{had} reconstruction and identification efficiencies drop significantly. Figure 2 shows the combined reconstruction and identification efficiencies of the standard ATLAS τ_{had} reconstruction and TauID algorithms as a function of $\Delta R_{\tau\tau}^{\text{gen,vis}}$ for generator-level 1-prong and 3-prong τ_{had} in $\tau_\mu\tau_{\text{had}}$ pairs. Here 'n-prong' denotes the number of charged hadrons that originate from the τ_{had} decay. The '$N_{\text{trk}}^{\text{reco}} = 1$ or 3' lines shows the efficiency of a generator-level 1-prong or 3-prong τ_{had} being reconstructed with the correct number of associated charged-particle tracks. The efficiency for a τ_{seed} jet to be reconstructed from a $\tau_\mu\tau_{\text{had}}$ pair remains high for all values of $\Delta R_{\tau\tau}^{\text{gen,vis}}$. However, the efficiencies for all standard TauID working points drop significantly in both the 1-prong and 3-prong cases when $\Delta R_{\tau\tau}^{\text{gen,vis}} < 0.4$. The tighter the working point, the greater the fractional loss in efficiency due to the presence of the nearby muon. The performance of the standard TauID algorithm is set as the baseline in this study.

The muon's nature as a minimum ionising particle, combined with the fact that its reconstruction is independent of its isolation [11], provides a motivation for excluding the ID track and calorimeter clusters associated with any nearby muon from the standard ATLAS τ_{had} reconstruction algorithm. By removing these contributions, the τ_{seed} jet would better represent only the $\tau_{\text{had-vis}}$, improving the accuracy of the TauID algorithm. Specifically, the ID track and clusters associated with a reconstructed muon that satisfies the 'Medium' muon identification working point are removed if the track or cluster is found within the reconstructed τ_{seed} jet. For calorimeter energy clusters, the algorithm checks if the energy of the cluster associated with the muon is compatible with the expected energy loss [43] from its interactions with the calorimeters between the ID and the MS and removes the cluster only when this is the case. After the muon removal, the standard τ_{had} reconstruction algorithm is re-run on the τ_{seed} jet. In this way, the relevant TauID variables for the τ_{had} candidate can be calculated without the muon component.

4.2 Performance of the method

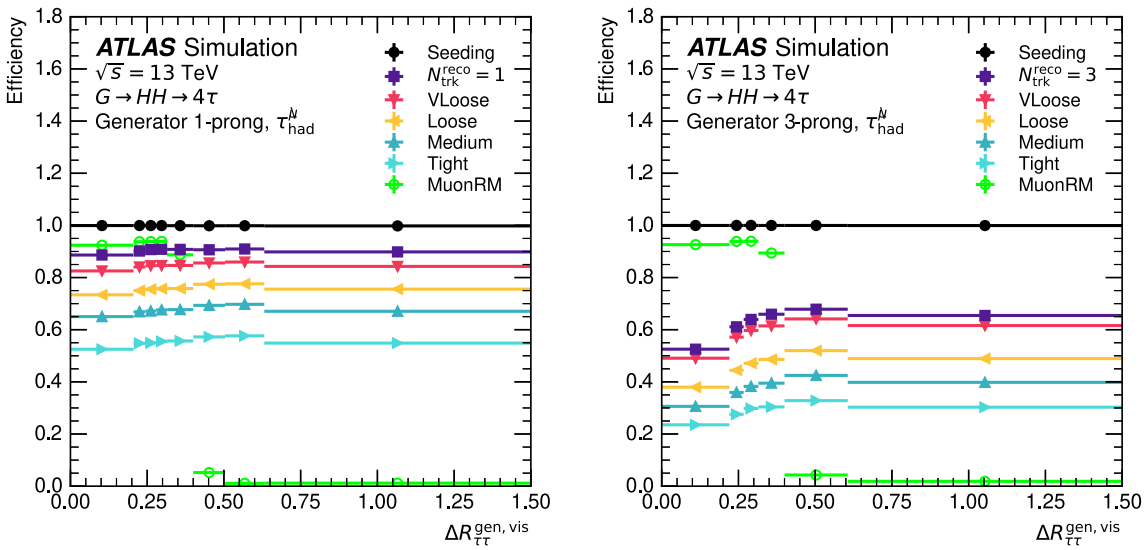
Figure 3 shows the combined reconstruction and identification efficiencies after the muon removal as a function of $\Delta R_{\tau\tau}^{\text{gen,vis}}$ for generator-level 1-prong and 3-prong $\tau_\mu\tau_{\text{had}}$ pairs for all working points. The reconstruction and identification efficiencies after the muon removal show a considerable improvement compared to those shown in Fig. 2. The signal efficiency is recovered almost completely for every working point for both 1-prong and 3-prong τ_{had}. In the 3-prong cases, the efficiency of TauID is limited by the accurate reconstruction of the correct number of tracks associated with the highly boosted τ_{had} candidates.

Roughly 95% of the τ_{seed} jets have a muon removed in the region where $\Delta R_{\tau\tau}^{\text{gen,vis}} < 0.4$. This can be expected given the 97% efficiency of the 'Medium' muon working point,



(a) (b)

Fig. 2 The combined reconstruction and identification efficiencies of the standard ATLAS TauID for generator-level **a** 1-prong and **b** 3-prong $\tau_\mu\tau_{\text{had}}$ pairs at all working points as a function of $\Delta R_{\tau\tau}^{\text{gen,vis}}$. The 'Seeding' line shows the efficiency of a τ_{seed} jet that matches a generator-level $\tau_\mu\tau_{\text{had}}$ pair being reconstructed; the '$N_{\text{trk}}^{\text{reco}} = 1$ or 3' line shows the efficiency of a generator-level τ_{had} being reconstructed with the correct number of associated charged-particle tracks. The 'VLoose', 'Loose', 'Medium', and 'Tight' lines show the efficiencies of the TauID working points



(a) (b)

Fig. 3 The combined reconstruction and TauID efficiencies after the muon removal for generator-level **a** 1-prong and **b** 3-prong $\tau_\mu\tau_{\text{had}}$ pairs at all working points as a function of $\Delta R_{\tau\tau}^{\text{gen,vis}}$. The 'Seeding' line shows the efficiency of a τ_{seed} jet that matches a generator-level $\tau_\mu\tau_{\text{had}}$ pair being reconstructed; the '$N_{\text{trk}}^{\text{reco}} = 1$ or 3' line shows the efficiency of a generator-level τ_{had} being reconstructed with the correct number of associated charged-particle tracks. The 'VLoose', 'Loose', 'Medium', and 'Tight' lines show the efficiencies of the TauID working points. The 'MuonRM' line shows the efficiency of a muon being identified and removed from the τ_{seed} jet. The transitions of the 'MuonRM' line between $0.35 < \Delta R_{\tau\tau}^{\text{gen,vis}} < 0.45$ is due to limited detector resolution in the direction of the reconstructed $\tau_{\text{had-vis}}$ and muon

with a dip below 90% in the region where the generator-level $|\eta|$ of the $\tau_{\text{had-vis}}$ is $|\eta|^{\text{gen,vis}} < 0.1$. This is illustrated in Fig. 4, which shows the signal efficiencies of the TauID working points after the muon removal as a function of $|\eta|^{\text{gen,vis}}$ for generator-level 1-prong and 3-prong τ_{seed} jets with $\Delta R_{\tau\tau}^{\text{gen,vis}} < 0.4$. The slight decrease in muon removal efficiency in the low $|\eta|^{\text{gen,vis}}$ region is caused by the non-instrumented regions of the MS.

The signal identification efficiencies at all working points of the standard ATLAS TauID are tuned to show minimum dependency on the generator-level p_{T} of the $\tau_{\text{had-vis}}$ ($p_{\text{T},\tau}^{\text{gen,vis}}$) and pile-up [5]. The stability of the TauID working point efficiencies, after the muon removal, against these variables are shown in Fig. 5. To focus on the objects of interest, only generator-level $\tau_\mu\tau_{\text{had}}$ pairs with the muon identified inside the τ_{seed} jet and removed ($\Delta R_{\tau\tau}^{\text{reco}} < 0.4$) are included in these plots. For comparison, the TauID working point efficiencies as a function of the same variables for τ_{seed} objects in which muon removal is not required ($\Delta R_{\tau\tau}^{\text{gen,vis}} > 0.45$) are shown in Fig. 6. Similar behaviour is observed in Figs. 5 and 6. The improved performance and good stability across different working points demonstrate that, after the muon removal, the TauID RNN receives as input the signal τ_{seed} jet as if it were a τ_{had} that is isolated (free from interference of surrounding particles).

After the removal of the overlapping muon, the precision with which the four-momentum of the τ_{seed} jet is reconstructed improves significantly. Figure 7a shows the distributions of the difference between the generated and reconstructed η (residuals) before and after the muon removal. Compared to the performance before muon removal, the η residuals that correspond to the 68% percentile (core resolution) improves by a factor of 15. The distributions of the $\tau_{\text{had-vis}}$ p_{T} residuals ($p_{\text{T}}/p_{\text{T}}^{\text{gen}}$) are shown in Fig. 7b. These results agree well with those reported for isolated τ_{had} in Ref. [44], further demonstrating the effectiveness of the muon removal method.

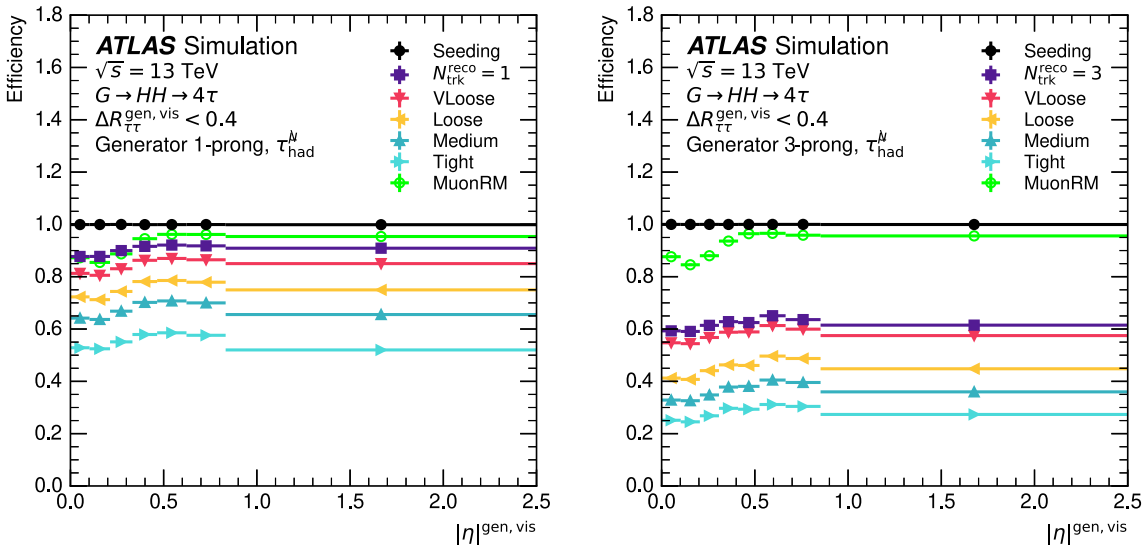
Having demonstrated that the reconstruction and identification efficiencies are significantly improved by the τ_{had}^{μ} method, the background rejection power is studied. The production of $t\bar{t}$ events is considered as a source of high-p_{T} heavy-flavour jets, which represents an example background to the τ_{had}^{μ} signal. The background rejection at the 'Medium' TauID working point, which is defined as the ratio of the total number of reconstructed τ_{had} candidates before muon removal to the number of false positives before or after muon removal, are shown in Fig. 8, as functions of the reconstructed $\tau_{\text{had-vis}}$ p_{T}. For the background rejection figures, the event selections are mostly based on the reconstructed properties instead of the generator-level information. A τ_{seed} jet reconstructed in the background sample is required to have reconstructed 20 GeV $< p_{\text{T}} <$ 300 GeV, $|\eta| < 2.5$, and to not be generator-matched to a τ_{had} from the semileptonic decay of a bottom or top quark. In addition, a reconstructed muon is required to be found inside the τ_{seed} jet. The τ_{had} candidates in which no muon is present are not considered in Fig. 8, as identical TauID results would be expected for these cases.

It is likely that after removing the muon, the number of reconstructed charged-particle tracks inside the τ_{seed} jet decreases by one compared to the standard reconstruction. Thus the background compositions of τ_{had} candidates reconstructed with the τ_{had}^{μ} method are different from the standard τ_{had} candidates. The background rejection power decreases slightly in the 3-prong case compared to the standard TauID algorithm. Without the presence of the muon within the τ_{seed} in the case of background events, the TauID algorithm finds it more challenging to reject semileptonic heavy-flavour jets. The 1-prong background rejection power increases slightly in the low-p_{T} region after removal of the muon due to fewer τ_{had} candidates being reconstructed after the muon removal.

The signal efficiency observed in the $G \to HH \to 4\tau$ samples and the background rejection power observed in the $t\bar{t}$ sample are combined to form the so-called receiver operating characteristic (ROC) curves. In addition to the same reconstruction level selections as the background τ_{seed} jets discussed previously, the τ_{seed} jets in the signal samples are required to be generator-matched to the $\tau_\mu\tau_{\text{had}}$ pairs. To minimise the bias introduced by the misalignment of the signal and background momentum spectra, the background events are reweighted so that the p_{T} distribution of the background sample matches that of the signal samples. The ROC curves illustrating the performance with and without muon removal are shown in Fig. 9. An order-of-magnitude performance gain is seen across the spectrum for both the 1-prong and 3-prong cases when the muon removal is applied.

To demonstrate the performance of the τ_{had}^{μ} method in reconstructing and identifying individual di-τ systems within the $G \to HH \to 4\tau$ process, Fig. 10 presents the combined τ_{had} reconstruction and identification efficiencies as a function of the generated graviton mass. The efficiencies correspond to the identification of individual di-τ systems originating from Higgs boson decays.

Compared to the standard ATLAS TauID algorithm, the τ_{had}^{μ} method demonstrates a complete recovery of the identification efficiency for both the 1-prong and 3-prong τ_{had} decays for high-mass $G \to HH \to 4\tau$ events, to the level expected for isolated τ_{had} candidates reconstructed with the standard TauID algorithm.



(a) (b)

Fig. 4 The combined reconstruction and TauID efficiencies after the muon removal for generator-level **a** 1-prong and **b** 3-prong $\tau_\mu\tau_{\text{had}}$ pairs at all working points as a function of $|\eta|^{\text{gen,vis}}$ for τ_{seed} jets with $\Delta R_{\tau\tau}^{\text{gen,vis}} < 0.4$. The 'Seeding' line shows the efficiency of a τ_{seed} jet that matches a generator-level $\tau_\mu\tau_{\text{had}}$ pair being reconstructed; the '$N_{\text{trk}}^{\text{reco}} = 1$ or 3' line shows the efficiency of a generator-level τ_{had} being reconstructed with the correct number of associated charged-particle tracks. The 'VLoose', 'Loose', 'Medium', and 'Tight' lines show the efficiencies of the TauID working points. The 'MuonRM' line shows the efficiency of a muon being identified and removed from the τ_{seed} jet

5 Validation of the $\tau_{\text{had}}^{\not\mu}$ method in the $Z \to \tau_\mu\tau_{\text{had}}$ final states

The $\tau_{\text{had}}^{\not\mu}$ method was developed for searches for high-mass BSM physics, such as the $G \to HH$ process, as described in Sect. 4. However, it is useful to validate its performance by considering a SM process and data from proton-proton collisions. In this paper, the Drell–Yan production of a Z boson in association with high-p_{T} jets from initial-state QCD radiation is considered as a validation process.

5.1 Z-boson kinematic reconstruction

The detector signature of the boosted $Z \to \tau_\mu\tau_{\text{had}}$ process includes one hadronically decaying τ-lepton and a muon, in association with significant missing transverse momentum ($\vec{p}_{\text{T}}^{\text{miss}}$) from the neutrinos produced in the two τ-lepton decays. The $\vec{p}_{\text{T}}^{\text{miss}}$, with magnitude $E_{\text{T}}^{\text{miss}}$, is estimated as the negative vector sum of the transverse momentum of all identified hard physics objects [45]. Tracks not associated with any such object are included in the soft term.

In this kinematic regime, the τ_{had} and the muon are likely to be reconstructed within the same τ_{seed} jet. In well measured events, the vector sum of the transverse momenta of the three neutrinos dominates the measured $\vec{p}_{\text{T}}^{\text{miss}}$, which in the azimuthal direction lies between the observed muon and the τ_{had} candidate in most cases. Also, on average, the $\vec{p}_{\text{T}}^{\text{miss}}$ should be closer in azimuth to the muon, because the τ_{lep} decay produces two neutrinos and the τ_{had} decay only one.

Without incorporating $\vec{p}_{\text{T}}^{\text{miss}}$, reconstructing the Z-boson invariant mass is not possible. However, it is possible to approximate the momenta of the neutrinos using the collinear approximation [46] as follows:

- the transverse momenta of the three neutrinos dominate the measured $\vec{p}_{\text{T}}^{\text{miss}}$, and other contributions are negligible;
- each τ-lepton is sufficiently boosted such that the neutrino (or pair of neutrinos) produced in its decay is collinear with its visible decay products.

These assumptions allow the reconstruction of the momenta of the neutrino (or pair of neutrinos) produced in the decay of each τ-lepton.[3]

Together with the momenta of the visible decay products, this procedure allows the momenta of the two τ-leptons,

[3] In events in which the $\vec{p}_{\text{T}}^{\text{miss}}$ lies outside the azimuthal angle between the visible decay products of the τ-leptons, the $\vec{p}_{\text{T}}^{\text{miss}}$ is projected onto the direction of the nearest visible decay, and the neutrino momentum associated with the other τ-lepton is set to zero. Furthermore, events for which collinear reconstruction is not possible, i.e., with $\vec{p}_{\text{T}}^{\text{miss}}$ deviating by more than 90° from the muon or the $\tau_{\text{had}}^{\not\mu}$ in $\Delta\phi$, are discarded.

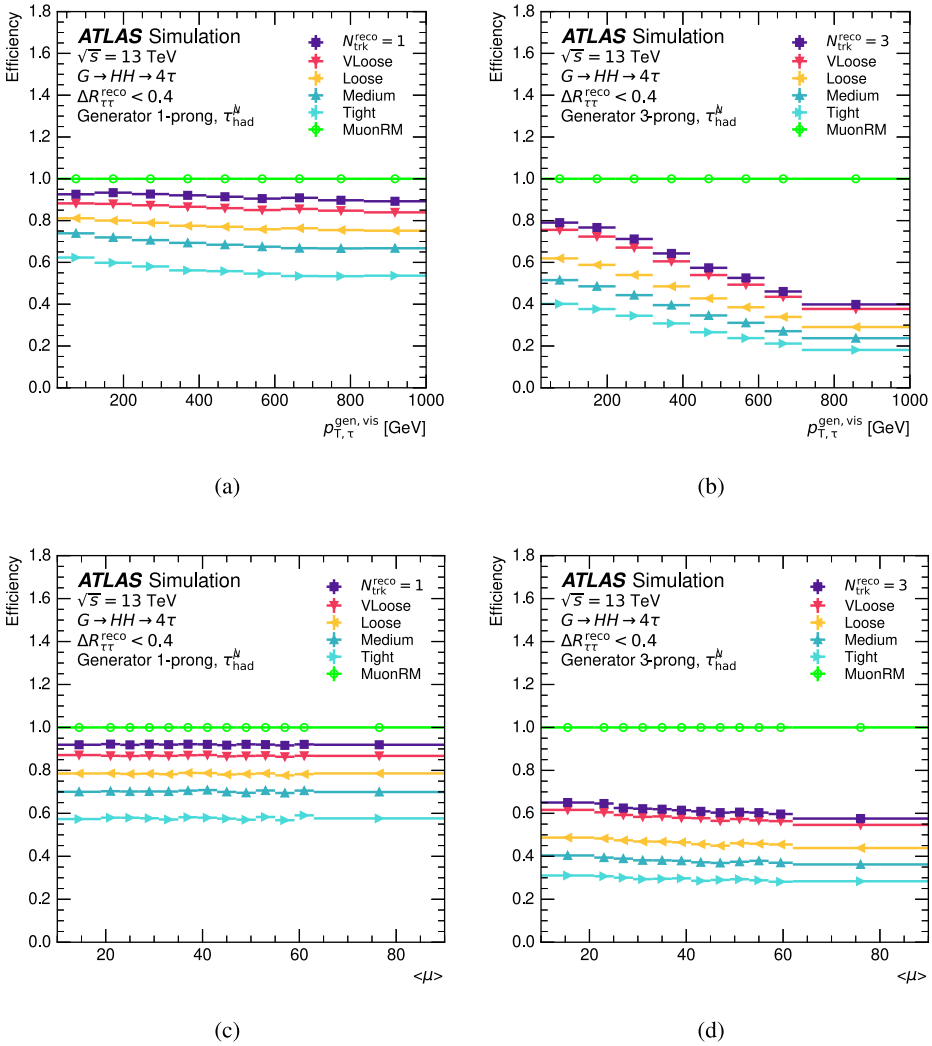


Fig. 5 The signal efficiencies of the TauID working points as a function of **a**, **b** the generator-level transverse momentum $p_{\mathrm{T},\tau}^{\mathrm{gen,vis}}$ and **c**, **d** the average number of interactions per bunch crossing $< \mu >$ for generator-level 1-prong and 3-prong τ_{seed} jets when the muon is identified inside the τ_{seed} jet and removed ($\Delta R_{\tau\tau}^{\mathrm{reco}} < 0.4$). The '$N_{\mathrm{trk}}^{\mathrm{reco}} = 1$ or 3' line shows the efficiency of a generator-level τ_{had} being reconstructed with the correct number of associated charged-particle tracks. The 'VLoose', 'Loose', 'Medium', and 'Tight' lines show the efficiencies of the TauID working points. The 'MuonRM' line shows the efficiency of a muon being identified and removed from the τ_{seed}, and is by definition 1.0 for all subfigures

and hence the transverse momentum ($p_{\mathrm{T}}^{\mathrm{col}}{}_{\mu-\mathrm{had}}$), and mass ($m_{\mu-\mathrm{had}}^{\mathrm{col}}$) of the system produced by the decay of the Z boson, to be reconstructed. The jets recoiling against the Z boson are reconstructed using the anti-k_t algorithm with a radius parameter $R = 0.4$ that uses particle flow objects [47] as input. These jets are then calibrated using simulation and data a to a precision of order 1% for central jets.

5.2 Event selection

Candidate events are required to have been triggered by an un-prescaled single-muon trigger [48] or an un-prescaled $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger [49]. The thresholds of the p_{T} required to fire each trigger varied for different data-taking periods. For the single muon trigger, the p_{T} requirement for triggers selecting isolated muons ranged from 20 to 26 GeV, while the p_{T} threshold for muon trigger without isolation requirements remained constant at 50 GeV. The $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers had a threshold of 70 GeV for the 2015 data-taking period and remained constant at 110 GeV for the rest of Run 2. Approximately 97% of $Z \to \tau_\mu \tau_{\mathrm{had}}$ simulated events that satisfy the final signal selection criteria satisfy the trigger selection.

For the signal region (SR) selection, events satisfying the trigger requirements are required to have at least one muon removal τ_{had} object which satisfies $p_{\mathrm{T}} > 15$ GeV, one or

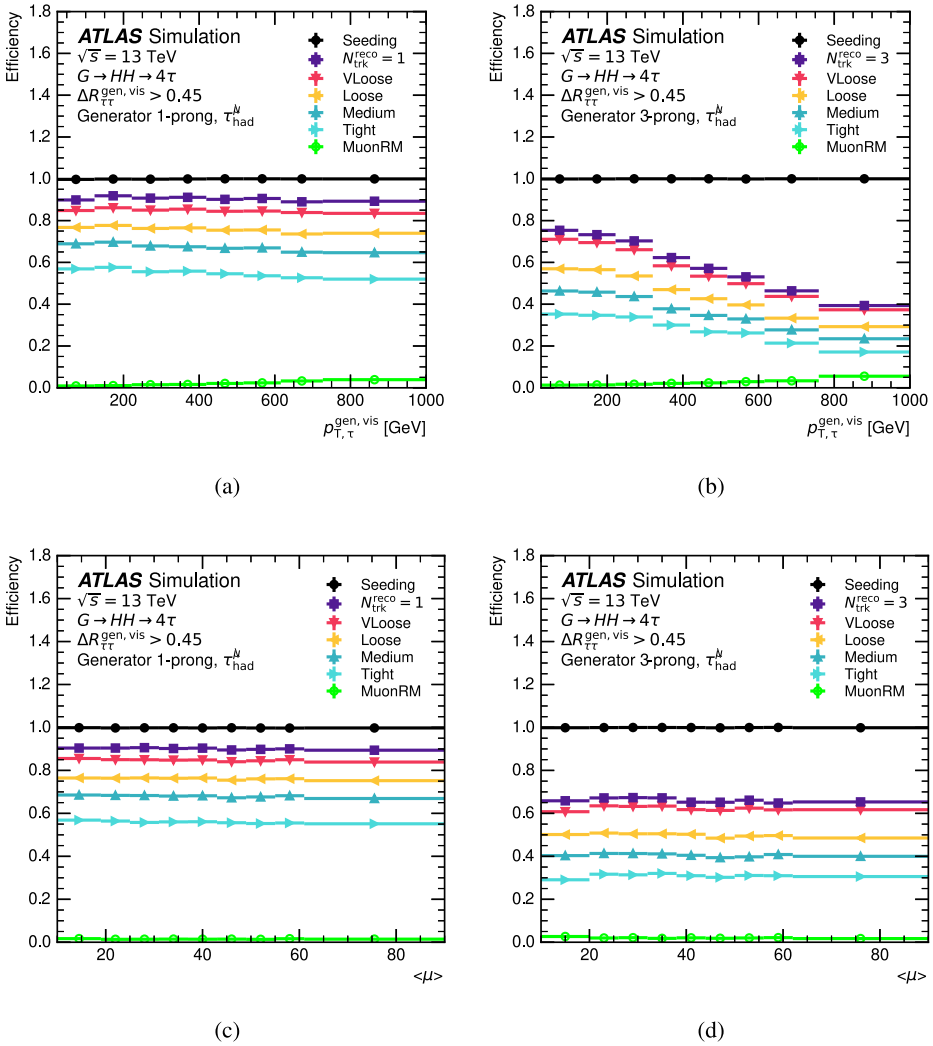


Fig. 6 The signal efficiencies of the TauID working points as a function of **a**, **b** the generator-level $p_{\mathrm{T},\tau}^{\mathrm{gen,vis}}$ and **c**, **d** the average number of interactions per bunch crossing ($<\mu>$) for the generator-level 1-prong and 3-prong τ_{seed} jets with $\Delta R_{\tau\tau}^{\mathrm{gen,vis}} > 0.45$. In this region, the muon removal should not affect the results. The 'Seeding' line shows the efficiency of a τ_{seed} jet that matches to a generator-level $\tau_\mu \tau_{\mathrm{had}}$ pair being reconstructed; the '$N_{\mathrm{trk}}^{\mathrm{reco}} = 1$ or 3' line shows the efficiency of a generator-level τ_{had} being reconstructed with the correct number of associated charged-particle tracks. The 'VLoose', 'Loose', 'Medium', and 'Tight' lines show the efficiencies of the TauID working points. The 'MuonRM' line shows the efficiency of a muon being identified and removed from the τ_{seed} jet, and is expected to be low in high $\Delta R_{\tau\tau}^{\mathrm{gen,vis}}$ region

three reconstructed charged-particle tracks with charge summing to one, and a TauID jet RNN score > 0.1, excluding $1.37 < |\eta| < 1.52$ and $|\eta| > 2.5$. This selection implies that at least one reconstructed muon satisfying the 'Medium' working point is inside the cone of each selected $\tau_{\mathrm{had}}^{\not\mu}$ candidate. Additionally, the muon must have $p_{\mathrm{T}} > 10$ GeV and opposite charge to the $\tau_{\mathrm{had}}^{\not\mu}$ candidate. In this study, the overlap removal between muons and τ_{had} candidates is turned off as the default overlap removal algorithm as described in Ref. [42] would remove some of the $\tau_{\mathrm{had}}^{\not\mu}$ candidates even if the muon removal method is successful. To suppress background from events containing heavy-flavour jets, events are rejected if they contain any jet that satisfies the DL1d based b-tagging algorithm at an 85% efficiency working point [50]. The signed $\Delta\phi$ between the muon and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ ($\Delta\phi_{\mu-\mathrm{MET}}^{\mathrm{signed}}$) is required to be $-0.1 < \Delta\phi_{\mu-\mathrm{MET}}^{\mathrm{signed}} < 0.4$. The sign of $\Delta\phi_{\mu-\mathrm{MET}}^{\mathrm{signed}}$ is determined by the direction of the $\tau_{\mathrm{had}}^{\not\mu}$ candidate. If the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is inside the opening angle of the muon and the τ_{had} candidate or if the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is outside the opening angle but closer to the muon, then the sign is positive; otherwise, it is negative. Since the focus of the analysis is the boosted $Z \to \tau_\mu \tau_{\mathrm{had}}$ process, a loose requirement $m_{\mu-\mathrm{had}}^{\mathrm{col}} > 40$ GeV, and a requirement $p_{\mathrm{T}\,\mu-\mathrm{had}}^{\mathrm{col}} > 250$ GeV

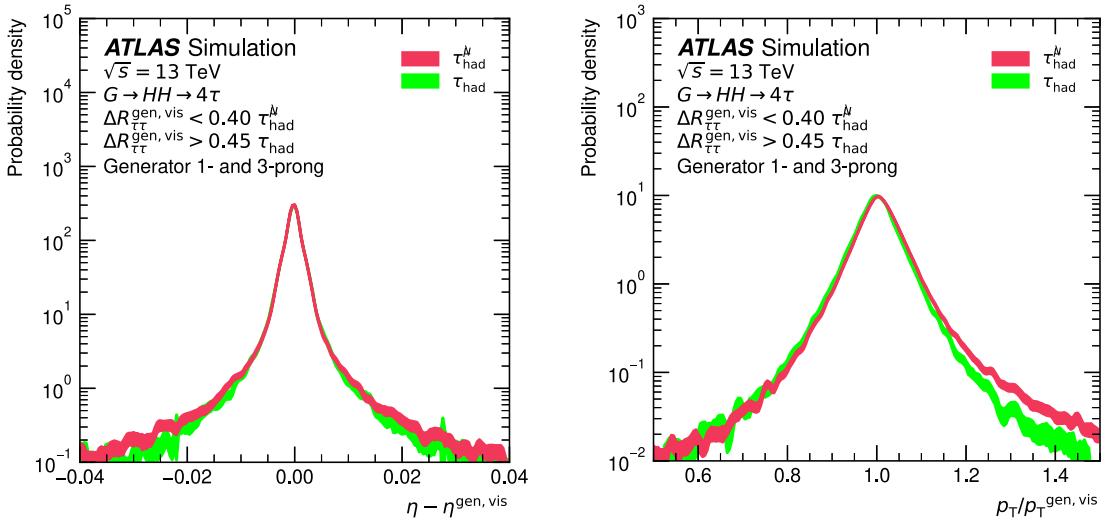


Fig. 7 The distributions of the residuals for **a** η and **b** p_{T} after calibrations with standard τ_{had} candidates and $\Delta R_{\tau\tau}^{\mathrm{gen,vis}} > 0.45$ and with $\tau_{\mathrm{had}}^{\mathrm{N}}$ candidates and $\Delta R_{\tau\tau}^{\mathrm{gen,vis}} < 0.4$. The bands represent the statistical uncertainties

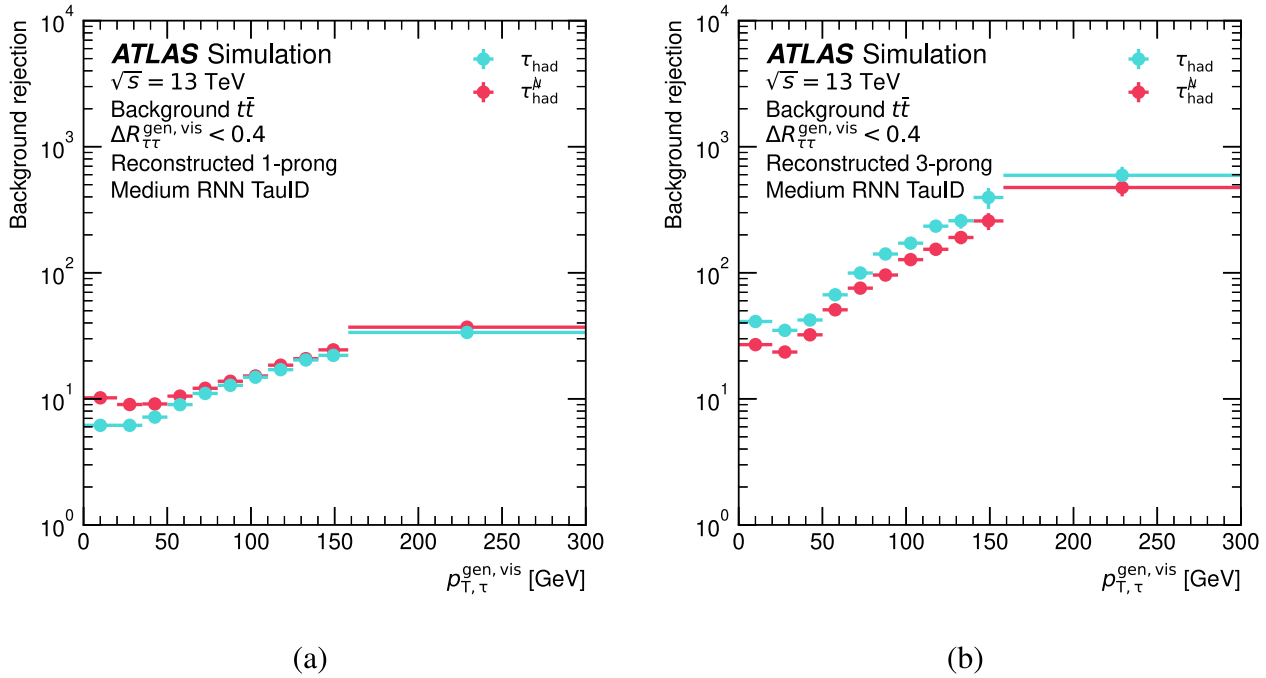


Fig. 8 The background rejection for τ_{seed} jets originating from semileptonic b-hadron decays in $t\bar{t}$ events at the 'Medium' TauID working point, as a function of the reconstructed p_{T} for **a** the reconstructed 1-prong candidates and **b** the reconstructed 3-prong candidates

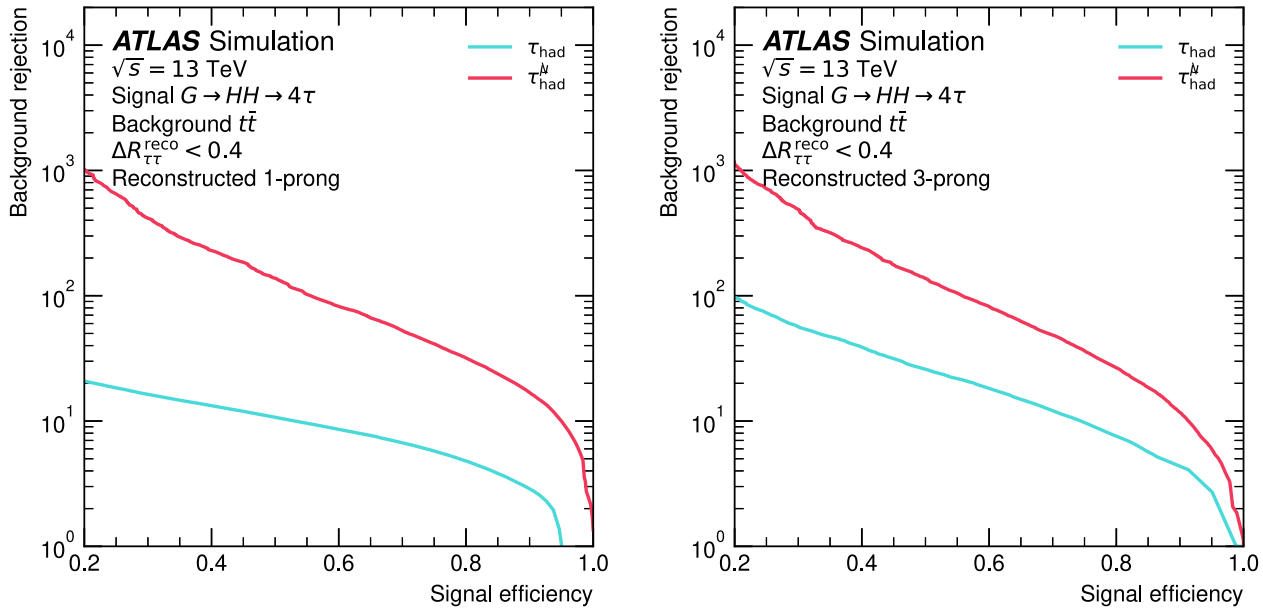


Fig. 9 Background rejection as a function of signal efficiency with and without muon removal for **a** the reconstructed 1-prong candidates and **b** the reconstructed 3-prong candidates. For the background sample, $t\bar{t}$ events are used. The combination of all $G \rightarrow HH \rightarrow 4\tau$ samples with m_G ranging from 1 to 5 TeV is used as the signal sample

are applied. A validation region (VR) is defined with the same selection requirements as the SR, except that the muon and $\tau_{\text{had}}^{\not\mu}$ candidate are required to have the same charge, and there is no requirement on $\Delta\phi_{\mu-\text{MET}}^{\text{signed}}$ or the number of jets satisfying the b-tagging criteria. The VR is designed with enough statistical power for testing the background modelling. These tests confirm that multi-jets events contribute negligibly to the background in both the SR and VR, making it an unlikely source of significant background mismodelling. Table 1 summarises the event selection requirements for the SR and VR respectively.

Figures 11 and 12 illustrate the distributions of the TauID jet RNN score and $p_{\text{T}}^{\text{col}}{}_{\mu-\text{had}}$ in the SR and VR. As shown in both figures, the data and MC predictions agree well in both the SR and VR. Due to the $m_{\mu-\text{had}}^{\text{col}} > 40$ GeV requirement, the kinematics of the selection produce a peak in the $p_{\text{T}}^{\text{col}}{}_{\mu-\text{had}}$ distribution around 500 GeV. This highlights the fact that the $\tau_{\text{had}}^{\not\mu}$ reconstruction picks up $\tau_\mu\tau_{\text{had}}$ pairs only with a sufficiently high boost.

5.3 Systematic uncertainties

The dominant source of systematic uncertainty in the comparison between the observed and expected yields in the SR is the modelling of the cross-section for Z-boson production. As discussed in Sect. 3, a +10% correction is applied to the predicted values for $Z(\rightarrow \tau\tau)$ + jets events, with the full size of this correction quoted as a systematic uncertainty. The most significant sources of experimental systematic uncertainties are related to TauID and τ-lepton energy scale (4%) [3,4], jet energy scale and resolution (2%) [51], $E_{\text{T}}^{\text{miss}}$ (2%) [45], and luminosity (0.83%) [35].

5.4 Results

To understand the performance improvement relative to the standard ATLAS τ_{had} reconstruction and identification, Fig. 13 shows multiple comparisons of the data and MC predictions for $m_{\mu-\text{had}}^{\text{col}}$ distributions corresponding to various signal selections; Fig. 13a corresponds to the SR selections defined in Sect. 5.2; Fig. 13b corresponds to the SR^{std}, which uses the standard ATLAS τ_{had} candidates, without the muon removal, but otherwise corresponds to the same event selection as the SR; Fig. 13c corresponds to the SR_{tight}, which imposes an additional 'Tight' RNN TauID requirement on the $\tau_{\text{had}}^{\not\mu}$ candidates, but otherwise corresponds to the SR selection; and Fig. 13d corresponds to the $\text{SR}_{\text{tight}}^{\text{std}}$, which imposes an additional 'Tight' RNN TauID requirement and uses the standard τ_{had} candidates, without muon removal.

The collinear mass reconstruction of the di-τ system is quite effective as it clearly shows the peak corresponding to

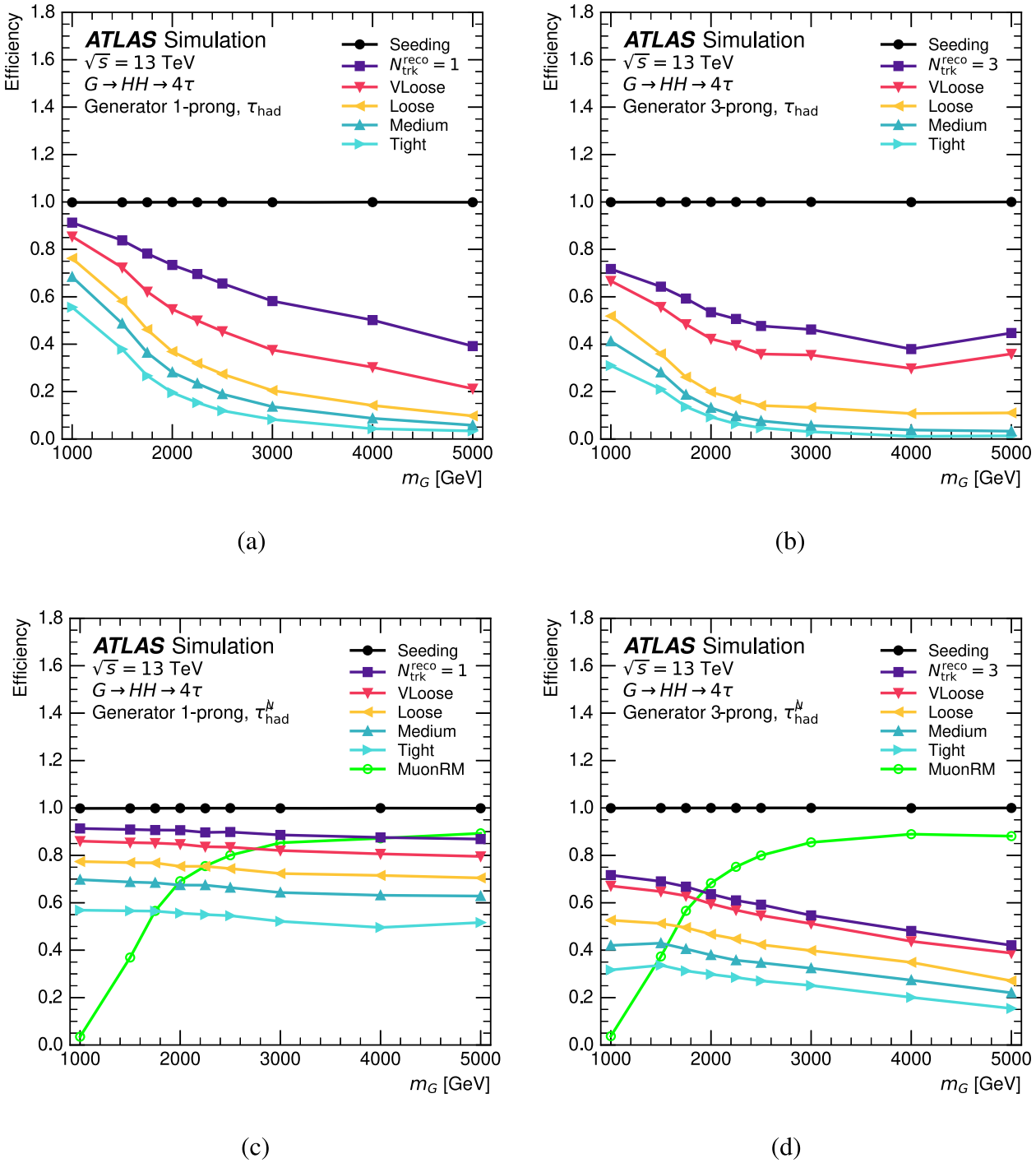


Fig. 10 The signal efficiencies of the TauID working points, as a function of m_G, for generator-level **a** 1-prong and **b** 3-prong τ_{had} with the standard ATLAS TauID algorithm and for generator-level **c** 1-prong and **d** 3-prong τ_{had} with the τ_{had}^{N} method. The efficiencies shown correspond to the identification of individual di-τ systems originating from Higgs boson decays. The 'Seeding' line shows the efficiency of a τ_{seed} jet that matches a generator-level $\tau_{\mu}\tau_{\text{had}}$ pair being reconstructed. The '$N_{\text{trk}}^{\text{reco}} = 1$ or 3' line shows the efficiency of a generator-level τ_{had} being reconstructed with the correct number of associated charged-particle tracks. The 'VLoose', 'Loose', 'Medium', and 'Tight' lines show the efficiencies of the TauID working points. The 'MuonRM' line shows the efficiency of a muon being identified and removed from the τ_{seed} jet

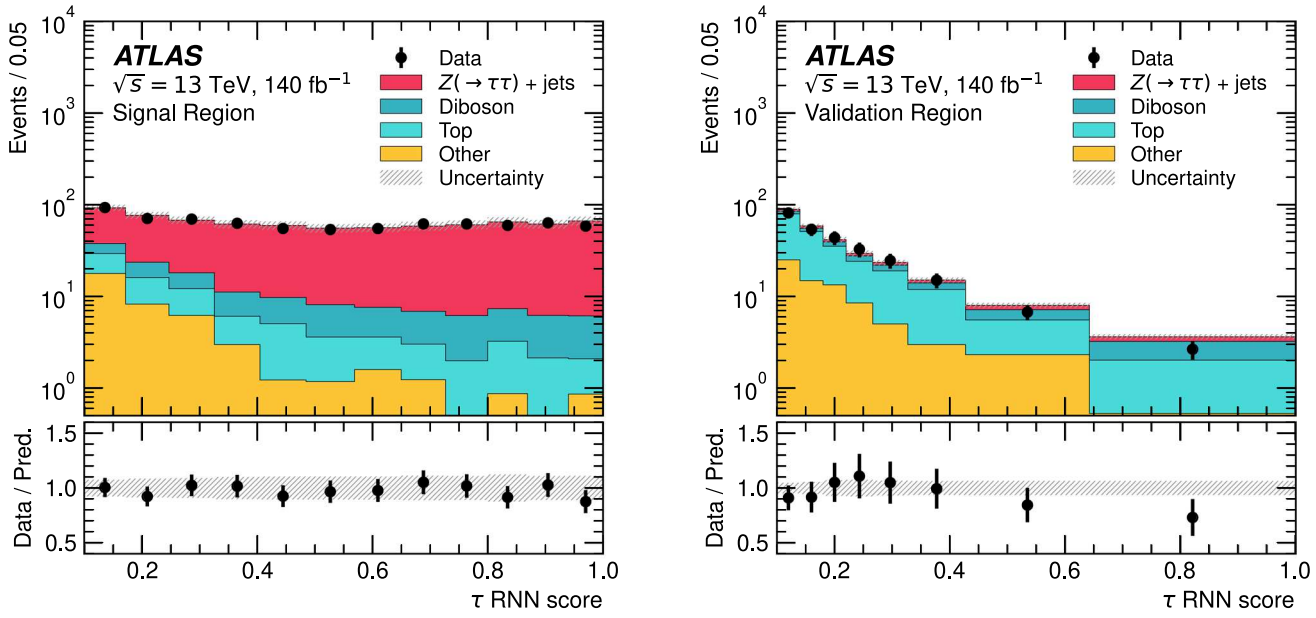


Fig. 11 The distribution of the TauID jet RNN score for $\tau_{\text{had}}^{\not{\text{k}}}$ **a** in the SR and **b** in the VR. '$Z(\rightarrow \tau\tau)$ + jets' represents the contributions from the signal process. 'Top' represents the predicted contributions from the $t\bar{t}$, single-top-quark, and tW processes. 'Diboson' indicates the contributions from WW, WZ, and ZZ processes. 'Other' includes the contributions from the $Z(\rightarrow \ell\ell)$+jets, W+jets, and Higgs boson processes. The uncertainties shown include both statistical and systematic sources

the Z boson mass in Fig. 13a. The shape of the $m_{\mu-\text{had}}^{\text{col}}$ distribution for signal Drell–Yan events is very different from that seen in inclusive production [52], with a much larger fraction of the signal events in the region 40 GeV $< m_{\mu-\text{had}}^{\text{col}} <$ 70 GeV compared to that at the Z boson peak. This pattern arises due to the steep fall in the $m_{\mu-\text{had}}^{\text{col}}$ distribution for Drell–Yan production, along with the narrowing opening angle of boosted $\tau_\mu\tau_{\text{had}}$ systems as $m_{\mu-\text{had}}^{\text{col}}$ decreases.

Table 2 shows the event yields in the data, as well as the predicted contributions from signal and background processes, corresponding to the various signal and validation selection criteria defined previously. Compared with the standard TauID, the $\tau_{\text{had}}^{\not{\text{k}}}$ method results in around three times more signal events in the SR, accompanied by an increase in the number of background events. In the SR_{tight} the number of signal events is about five times higher than when using

Table 1 Summary of event selection requirements

Object	Signal region	Validation region
$\tau_{\text{had}}^{\not{\text{k}}}$ candidate	$p_{\text{T}} > 15$ GeV	$p_{\text{T}} > 15$ GeV
	TauID jet RNN score > 0.1	TauID jet RNN score > 0.1
	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.5$	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.5$
	1 or 3 charged-particle tracks	1 or 3 charged-particle tracks
Muon	'Medium' working point	'Medium' working point
	$p_{\text{T}} > 10$ GeV	$p_{\text{T}} > 10$ GeV
$\tau_\mu\tau_{\text{had}}$ pair	no b-tagged jet at 85% efficiency working point	–
	$-0.1 < \Delta\phi_{\mu-\text{MET}}^{\text{signed}} < 0.4$	–
	$m_{\mu-\text{had}}^{\text{col}} > 40$ GeV	$m_{\mu-\text{had}}^{\text{col}} > 40$ GeV
	$p_{\text{T}}{}_{\mu-\text{had}}^{\text{col}} > 250$ GeV	$p_{\text{T}}{}_{\mu-\text{had}}^{\text{col}} > 250$ GeV
	opposite charge muon and $\tau_{\text{had}}^{\not{\text{k}}}$ candidates	**same charge** muon and $\tau_{\text{had}}^{\not{\text{k}}}$ candidates

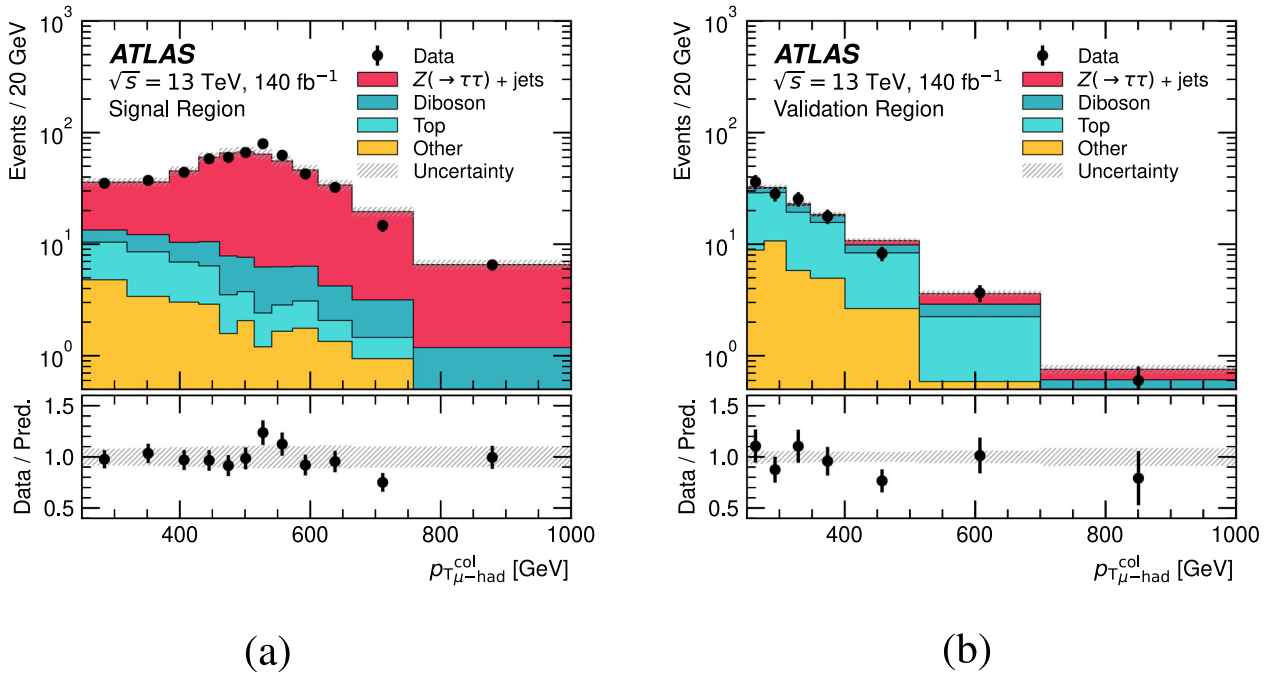


Fig. 12 The distribution of the $p_{\mathrm{T}\mu-\mathrm{had}}^{\mathrm{col}}$ **a** in the SR, and **b** in the VR. '$Z(\rightarrow \tau\tau)+$jets' represents the contributions from the signal process. 'Diboson' indicates the contributions from WW, WZ, and ZZ processes. 'Top' represents the predicted contributions from the $t\bar{t}$, single-top-quark, and tW processes. 'Other' includes the contributions from the $Z(\rightarrow \ell\ell)$+jets, W+jets, and Higgs boson processes. The uncertainties shown include both statistical and systematic sources

the standard τ_{had} candidates, with a corresponding rise in background events as well.

Subtracting the expected background yield in the SR of 223 ± 5 events gives a measured yield for $Z \rightarrow \tau_\mu \tau_{\mathrm{had}}$ of 920 ± 34 events. This can be compared with the expected yield for $Z \rightarrow \tau_\mu \tau_{\mathrm{had}}$ of 945 ± 8 (stat.) ± 114 (syst.) events. Adding all sources of statistical and systematic uncertainty results in a total uncertainty of 12%. The same calculations are performed in the $\mathrm{SR}_{\mathrm{tight}}$. The ratio of data to prediction is 0.97 ± 0.12 in the SR, and 0.96 ± 0.12 in the $\mathrm{SR}_{\mathrm{tight}}$.

6 Conclusions

In this paper, the reconstruction of a highly boosted pair of τ-leptons is considered, in which one τ-lepton decays into a muon plus two neutrinos and the other τ-lepton decays hadronically, with the visible decay products overlapping. In such cases, the standard ATLAS reconstruction and identification algorithms for hadronically decaying τ-leptons fail due to the presence of the nearby muon.

The development of a muon removal procedure for τ_{had} candidates (denoted $\tau_{\mathrm{had}}^{\not\mu}$) using samples of high-mass $G \rightarrow HH \rightarrow 4\tau$ events is described. The $\tau_{\mathrm{had}}^{\not\mu}$ method recovers the τ_{had} reconstruction and identification efficiencies to the expected level for isolated τ_{had} decays at all τ-lepton identification working points. The measurement precision for the charge and kinematic properties of the visible τ_{had} system is similarly recovered. The background rejection power is studied using heavy-flavour jets from top-quark decays and shows no degradation relative to the standard algorithm for τ_{had} identification. The $\tau_{\mathrm{had}}^{\not\mu}$ method is validated by selecting a sample of highly boosted $Z \rightarrow \tau_\mu \tau_{\mathrm{had}}$ final states using a data set of proton–proton collisions at $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the LHC, and corresponding to an integrated luminosity of 140 fb^{-1}. Good agreement is found between data and simulation in both the $Z \rightarrow \tau_\mu \tau_{\mathrm{had}}$ signal region and a background-rich validation region. The ratio of the observed and predicted event yields in the signal region is found to be consistent with unity within an uncertainty of 12%.

The results presented in this paper demonstrate the effectiveness of the $\tau_{\mathrm{had}}^{\not\mu}$ method in enhancing the signal sensitivity of the boosted $\tau_\mu \tau_{\mathrm{had}}$ channel. The observed good agreement between data and simulation in the $Z \rightarrow \tau_\mu \tau_{\mathrm{had}}$ signal region reaffirms the robustness of the newly developed reconstruction method.

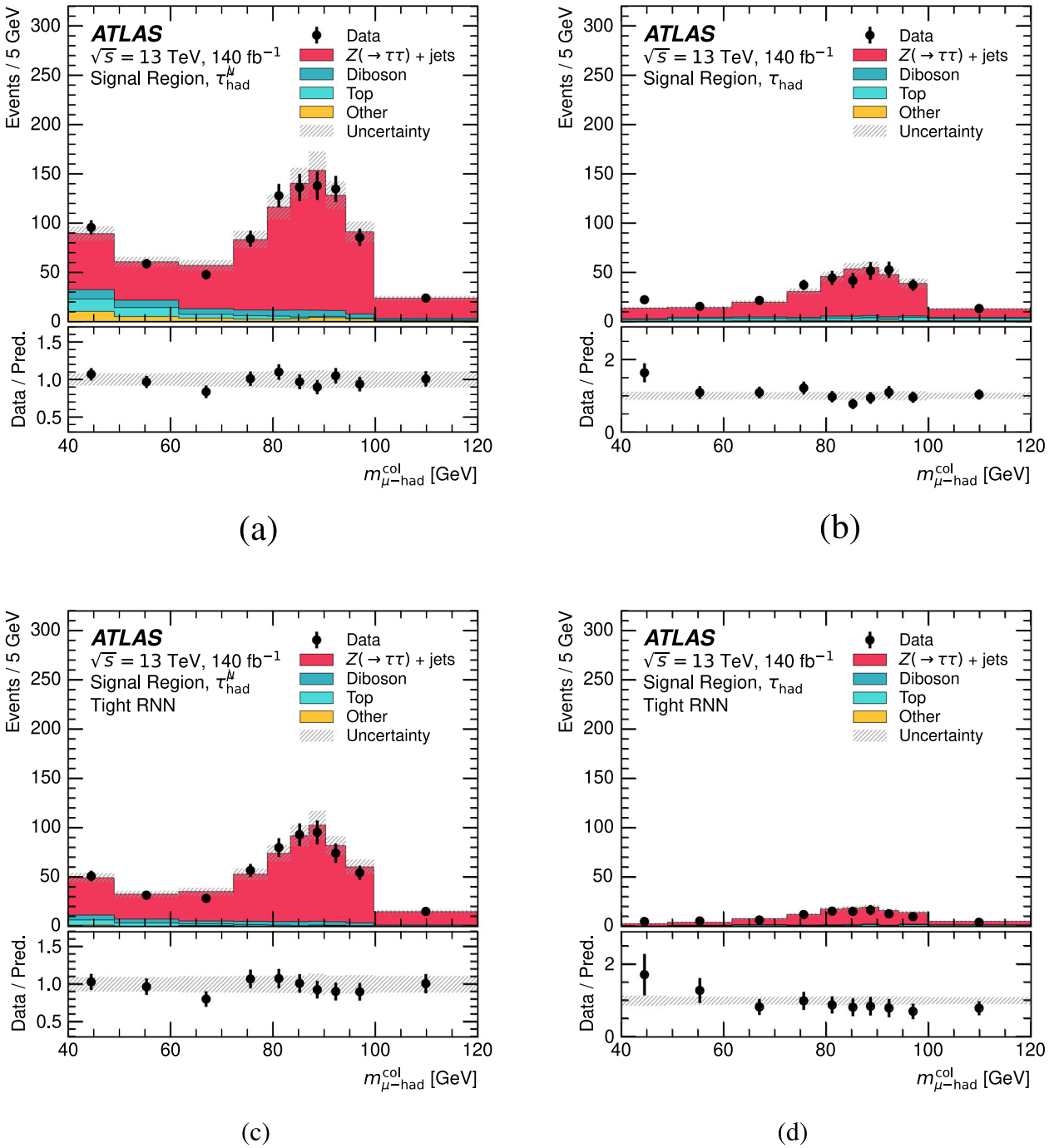


Fig. 13 The distributions of $m^{\text{col}}_{\mu-\text{had}}$ corresponding to the various signal region selection criteria defined in the text: **a** SR, **b** SR^{std}, **c** SR_{tight}, and **d** $\text{SR}^{\text{std}}_{\text{tight}}$. '$Z(\rightarrow \tau\tau)$ + jets' represents the contributions from the signal process. 'Diboson' indicates the contributions from WW, WZ, and ZZ processes. 'Top' represents the predicted contributions from the $t\bar{t}$, single-top-quark, and tW processes. 'Other' includes the contributions from the $Z(\rightarrow \ell\ell)$+jets, W+jets, and Higgs boson processes. The uncertainties shown include both statistical and systematic sources

Table 2 Event yields for different event selection criteria, as defined in the text. The uncertainties quoted are statistical only

	SR	SR^{std}	SR_{tight}	SR^{std}_{tight}	VR
$Z \to \tau\tau$	945 ± 8	325 ± 4	633 ± 7	117 ± 2	20 ± 1
Diboson	91 ± 1	25 ± 1	50 ± 1	9 ± 0	38 ± 1
Top	68 ± 3	53 ± 3	26 ± 2	21 ± 2	164 ± 5
Other	65 ± 4	17 ± 2	12 ± 2	5 ± 1	76 ± 4
Total predicted	1168 ± 10	420 ± 5	721 ± 8	153 ± 3	297 ± 7
Data	1143	435	698	133	281

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The specific code and configurations written in support of this analysis are not public; however, these are internally preserved.]

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