



# Search for dark matter produced in association with a single top quark in $\sqrt{s} = 13$ TeV $pp$ collisions with the ATLAS detector

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**Abstract** This paper presents a search for dark matter in the context of a two-Higgs-doublet model together with an additional pseudoscalar mediator,  $a$ , which decays into the dark-matter particles. Processes where the pseudoscalar mediator is produced in association with a single top quark in the 2HDM+ $a$  model are explored for the first time at the LHC. Several final states which include either one or two charged leptons (electrons or muons) and a significant amount of missing transverse momentum are considered. The analysis is based on proton–proton collision data collected with the ATLAS experiment at  $\sqrt{s} = 13$  TeV during LHC Run 2 (2015–2018), corresponding to an integrated luminosity of  $139 \text{ fb}^{-1}$ . No significant excess above the Standard Model predictions is found. The results are expressed as 95% confidence-level limits on the parameters of the signal models considered.

## 1 Introduction

Strong evidence for the existence of a new, non-luminous matter component of the universe, dark matter (DM), arises from astrophysical observations such as precise measurements of the cosmic microwave background and from gravitational lensing measurements. Through its gravitational interactions, it is suggested that DM constitutes up to 26% of the matter–energy content of the universe [1,2]. The nature and properties of DM remain largely unknown in the context of the Standard Model (SM) of particle physics. Under the hypothesis that DM behaves like a weakly interacting massive particle (WIMP) [3], searches are performed using multiple, complementary approaches. At hadron colliders, searches for WIMP-like DM production crucially rely on one or more visible particles being produced in association with the sought-after invisible DM candidate. The experimental signature for DM candidates is missing transverse momentum ( $\vec{p}_T^{\text{miss}}$ , its modulus denoted by  $E_T^{\text{miss}}$ ) in collision events. Several models have been proposed in the past decades, with

the details of the DM–SM production process depending on the model assumptions.

A class of simplified models for DM searches at the LHC is considered in this paper. It involves a two-Higgs-doublet extended sector together with an additional pseudoscalar mediator to DM, the 2HDM+ $a$  model [4,5]. This class of models represents one of the simplest ultraviolet-complete and renormalisable frameworks for investigating the broad phenomenology predicted by spin-0 mediator-based DM models [5–19]. For the present study, a type-II [20,21] coupling structure of the Higgs sector to third-generation fermions is considered. The CP eigenstates are identified with the mass eigenstates, i.e. two scalars  $h$  and  $H$ , two pseudoscalars  $A$  and  $a$ , and charged scalars  $H^\pm$ . Three mixing angles are defined in the model:  $\alpha$  denotes the mixing angle between the two CP-even weak spin-0 eigenstates,  $\tan \beta$  is the ratio of the vacuum expectation values (VEVs) of the two Higgs doublets and  $\theta$  represents the mixing angle of the two CP-odd weak spin-0 eigenstates. The alignment ( $\cos(\beta - \alpha) = 0$ ) and decoupling limit is assumed, such that the lightest CP-even state of the Higgs sector,  $h$ , can be identified with the SM Higgs boson and the electroweak VEV is set to 246 GeV. The pseudoscalar mediator  $a$  couples the DM particles,  $\chi$ , to the SM and mixes with the pseudoscalar partner of the SM Higgs boson,  $A$ . Following the prescriptions in Ref. [5], the masses of the heavy CP-even Higgs boson  $H$  and charged bosons  $H^\pm$  are set equal to the mass of the heavy CP-odd partner  $A$ .

This set of models offers a rich phenomenology, with a variety of final states that might arise depending on the production and decay modes of the various bosons composing the Higgs sector, as investigated in Ref. [22]. A recent study [23] has shown that final-state events characterised by the presence of  $E_T^{\text{miss}}$  and a single top quark provide promising sensitivity to 2HDM+ $a$  models. As in SM single top production, three different types of processes contribute at leading order (LO) in QCD:  $t$ -channel production,  $s$ -channel production and associated production with a  $W$  boson ( $tW$ ). In the following, these are collectively referred to as DMt

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processes. The  $t$ -channel process  $pp \rightarrow tj\chi\bar{\chi}$  receives its dominant contributions from the two diagrams shown in Fig. 1 a, b. These two diagrams interfere destructively, ensuring the perturbative unitarity of the  $pp \rightarrow tj\chi\bar{\chi}$  process. The magnitude of the interference decreases with increasing  $H^\pm$  mass. In the case of the  $tW$  production channel, the two diagrams shown in Fig. 1 c, d provide the dominant contributions to the  $DMt$  cross section. As in  $t$ -channel production, these two diagrams interfere destructively. When the decays  $H^\pm \rightarrow W^\pm a$  are kinematically possible, the charged Higgs bosons are produced on-shell and the cross section of  $pp \rightarrow tW\chi\bar{\chi}$ , assuming  $H^\pm$  masses of a few hundred GeV, increases to produce a sizeable event rate. Finally,  $s$ -channel production is relevant in regions of the parameter space characterised by low  $H^\pm$  masses ( $< 300$  GeV) and it is not directly targeted by the analysis, but its contribution to the signal is taken into account.

This paper presents a dedicated search for single top quarks produced in association with DM candidates, exploiting final-state signatures characterised by the presence of: large  $E_T^{\text{miss}}$ ; jets, possibly arising from the fragmentation of  $b$ -hadrons ( $b$ -jets); and one or two charged leptons, either electrons or muons ( $\ell = e, \mu$ ). The analysis is conducted using proton–proton ( $pp$ ) collisions at a centre-of-mass energy  $\sqrt{s} = 13$  TeV produced at the LHC and collected by ATLAS between 2015 and 2018, for a dataset corresponding to  $139 \text{ fb}^{-1}$ . Three analysis channels, characterised by different lepton or jet multiplicities, are optimised to target different processes:  $tW_{1L}$  and  $tW_{2L}$  (single-lepton and dilepton final states, respectively) for the  $tW$ +DM events and  $tj_{1L}$  for  $t$ -channel DM production. The results are interpreted in the context of 2HDM+ $a$  models, considering various assumptions about the most relevant parameters,  $m_a$ ,  $m_{H^\pm}$ , and  $\tan\beta$ . Furthermore, the mutually exclusive  $tW_{1L}$  and  $tW_{2L}$  analysis channels are statistically combined to maximise the sensitivity to  $tW$ +DM processes.

Previous searches for 2HDM+ $a$  models targeted associated production of DM candidates with Higgs or  $Z$  bosons [24], as well as DM and a  $t\bar{t}$  pair (referred to as  $DMt\bar{t}$ ) (see Ref. [25] for CMS and Ref. [22] and references therein for ATLAS). This search is targeting the unexplored models within ATLAS where DM produced in association with single top quarks (for CMS results, see Ref. [26]). The analysis is also sensitive to  $DMt\bar{t}$  processes in regions of the parameter space where the  $DMt$  and  $DMt\bar{t}$  production rates are similar.

## 2 ATLAS detector

The ATLAS detector [27] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry

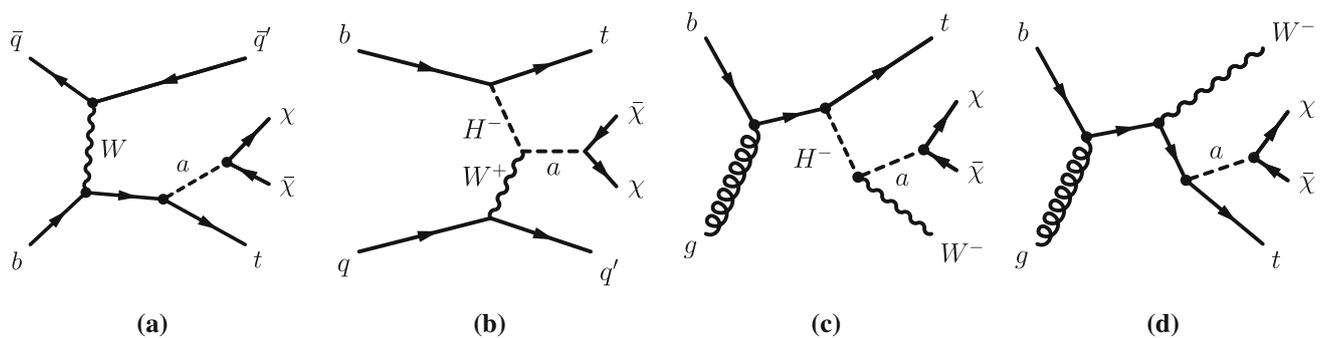
and nearly  $4\pi$  coverage in solid angle.<sup>1</sup> The inner tracking detector consists of pixel and microstrip silicon detectors covering the pseudorapidity region  $|\eta| < 2.5$ , surrounded by a transition radiation tracker which enhances electron identification in the region  $|\eta| < 2.0$ . A new inner pixel layer, the insertable B-layer [28, 29], was added at a mean radius of 3.3 cm during the period between Run 1 and Run 2 of the LHC. The inner detector is surrounded by a thin superconducting solenoid providing an axial 2 T magnetic field and by a fine-granularity lead/liquid-argon (LAr) electromagnetic calorimeter covering  $|\eta| < 3.2$ . A steel/scintillator-tile calorimeter provides hadronic coverage in the central pseudorapidity range ( $|\eta| < 1.7$ ). The endcap and forward regions ( $1.5 < |\eta| < 4.9$ ) of the hadron calorimeter are made of LAr active layers with either copper or tungsten as the absorber material. A muon spectrometer with an air-core toroid magnet system surrounds the calorimeters. Three layers of high-precision tracking chambers provide coverage in the range  $|\eta| < 2.7$ , while dedicated fast chambers allow triggering in the region  $|\eta| < 2.4$ . The ATLAS trigger system consists of a hardware-based level-1 trigger followed by a software-based high-level trigger [30].

## 3 Data and Monte Carlo simulation

The data analysed in this paper correspond to an integrated luminosity of  $139 \text{ fb}^{-1}$  of  $pp$  collision data collected between 2015 and 2018 by the ATLAS detector with a centre-of-mass energy of 13 TeV and a 25 ns proton bunch crossing interval. The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [31], obtained using the LUCID-2 detector [32] for the primary luminosity measurements. All detector subsystems were required to be operational during data taking. The average number of interactions in the same and nearby bunch crossings (pile-up) increased from  $\langle\mu\rangle = 13.4$  (2015 dataset) to  $\langle\mu\rangle = 36.1$  (2018 dataset), with a highest  $\langle\mu\rangle = 37.8$  (2017 dataset) and an average  $\langle\mu\rangle = 33.7$ .

Candidate events were recorded using a combined set of triggers [30] based on the presence of missing transverse momentum or charged leptons ( $\ell = e, \mu$ ). The  $E_T^{\text{miss}}$  trigger [33] is fully efficient for events with reconstructed

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector. The positive  $x$ -axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive  $y$ -axis pointing upwards, while the beam direction defines the  $z$ -axis. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. The pseudorapidity  $\eta$  is defined in terms of the polar angle  $\theta$  by  $\eta = -\ln \tan(\theta/2)$ . Rapidity is defined as  $y = 0.5 \ln[(E + p_z)/(E - p_z)]$  where  $E$  denotes the energy and  $p_z$  is the component of the momentum along the beam direction. The angular distance  $\Delta R$  is defined as  $\sqrt{(\Delta y)^2 + (\Delta\phi)^2}$ .



**Fig. 1** Representative diagrams of the dark-matter particle  $\chi$  pair production from the 2HDM+ $a$  model considered in this analysis: **a**, **b** through the  $t$ -channel, and **c**, **d** through the  $tW$  channel

$E_T^{\text{miss}} > 250$  GeV and it was used for the single-lepton analysis channels. Furthermore, an OR between  $E_T^{\text{miss}}$  and single-lepton triggers was used for the  $t_{\text{JL}}$  channel for events with reconstructed  $E_T^{\text{miss}} < 250$  GeV. Triggers based on a single muon (electron) require the presence of a muon (electron) with transverse momentum  $p_T$  (transverse energy  $E_T$ ) above certain thresholds, and impose data quality and lepton isolation requirements. The lowest  $p_T$  ( $E_T$ ) threshold without trigger prescaling is 24 (26) GeV for muons (electrons) and includes a lepton isolation requirement that is not applied for triggers with higher thresholds. In the two-lepton channel, lower thresholds for electrons and muons must be applied to retain sensitivity to the signal. A combined set of two-lepton triggers was used, with the muon (electron)  $p_T$  ( $E_T$ ) trigger threshold depending on the data-taking period. The lepton trigger threshold ranged between 8 and 22 GeV for muons, and between 12 and 24 GeV for electrons. The analysis selections are chosen to guarantee maximum trigger efficiency, generally above 95%. Trigger matching requirements [30] are applied where the lepton(s) must lie in the vicinity of the corresponding trigger-level object.

Dedicated Monte Carlo (MC) simulated samples are used to model SM processes and estimate the expected signal yields. All samples were produced using the ATLAS simulation infrastructure [34] and GEANT4 [35], or a faster simulation based on a parameterisation of the calorimeter response and GEANT4 for the other detector systems [34]. The simulated events are reconstructed with the same algorithms as used for data. They contain a realistic modelling of pile-up interactions with pile-up profiles matching the ones of each dataset between 2015 and 2018, obtained by overlaying minimum-bias events simulated using the soft QCD processes of PYTHIA 8.186 [36] with the NNPDF2.3 LO set of parton distribution functions (PDFs) [37] and the A3 [38] set of tuned parameters (tune).

Signal MC samples for single top quark production in association with DM include  $tW$ ,  $t$ -channel and  $s$ -channel processes. Samples were produced either varying the  $(m_a, m_{H^\pm})$  parameters and assuming  $\tan\beta$  equal to

unity, or varying the  $(\tan\beta, m_{H^\pm})$  parameters and setting  $m_a = 250$  GeV. Details of other parameter value assumptions are provided in Sect. 7. The samples were generated from leading-order (LO) matrix elements using the MADGRAPH5\_aMC@NLO [39] v2.6.2 generator interfaced to PYTHIA 8.212 [40] with the A14 tune [41] for the modelling of parton showering (PS), hadronisation and the description of the underlying event. Parton luminosities are provided by the five-flavour scheme NNPDF3.0 NLO [42] PDF set. Signal cross sections are calculated to LO accuracy in QCD. Additional simulated samples are used for  $DMt\bar{t}$  processes. They were generated using LO matrix elements, with up to one extra parton using the MADGRAPH5\_aMC@NLO v2.6.7 generator interfaced to PYTHIA 8.244 with the same PDF set and tune as used for the  $tW$ ,  $t$ - and  $s$ -channel processes. The top quark decay was simulated using MADSPIN [43]. In this case, signal cross sections are calculated to next-to-leading-order (NLO) accuracy using the same version of MADGRAPH5\_aMC@NLO as suggested in Ref. [16].

Background samples were simulated using different MC event generators, accurate at NLO or higher order, depending on the process. All background processes are normalised to the best available theoretical calculation of their respective cross sections. The event generators, the accuracy of theoretical cross sections, the underlying-event parameter tunes, and the PDF sets used in simulating the SM background processes most relevant for this analysis are summarised in Table 1. For all samples, except those generated using SHERPA [44–48], the EVTGEN v1.2.0 [49] program was used to simulate the properties of the  $b$ - and  $c$ -hadron decays.

#### 4 Event reconstruction and object definitions

Common event-quality criteria and object reconstruction definitions are applied for all analysis channels, including standard data-quality requirements to select events taken during optimal detector operation. In addition, in each analysis channel, dedicated selection criteria, which are specific to

**Table 1** List of generators used for the different SM background processes. Diboson includes  $WW$ ,  $WZ$  and  $ZZ$  production. Information is given about the underlying-event tunes, the PDF sets and the perturbative QCD highest-order accuracy (LO, NLO, next-to-next-to-leading

order (NNLO), and next-to-next-to-leading-log (NNLL)) used for the normalisation of the different samples. Diboson cross sections are taken directly from SHERPA

Process	Generator	PDF set	PS and frag./hadr.	UE tune	Cross-section accuracy	
Top pair ( $t\bar{t}$ )	POWHEG-BOX v2 [50–53]	NNPDF 3.0 NLO	PYTHIA 8	A14	NNLO+NNLL [54]	
Single-top	$t$ -channel	POWHEG-BOX v1 [55]	NNPDF 3.0 NLO	PYTHIA 8	A14	NNLO+NNLL [56]
	$s$ - and $Wt$ -channel	POWHEG-BOX v2 [57]	NNPDF 3.0 NLO	PYTHIA 8	A14	NNLO+NNLL [58, 59]
$V$ +jets ( $V = W/Z$ )	SHERPA 2.2.1 [44–48]	NNPDF 3.0 NNLO	SHERPA	Default	NNLO [60]	
Diboson	SHERPA 2.2.1 or 2.2.2	NNPDF 3.0 NNLO	SHERPA	Default	NLO	
$t\bar{t} + V$ , $V = W, Z, h$	MADGRAPH5_aMC@NLO 2.3.3	NNPDF 3.0 NLO	PYTHIA 8	A14	NLO [39, 61]	
$tWZ$	MADGRAPH5_aMC@NLO 2.6.7	NNPDF 3.0 NLO	PYTHIA 8	A14	NLO [39]	

the objects and kinematics of interest in those final states, are applied as described in Sect. 5.

Events are required to have at least one reconstructed interaction vertex with a minimum of two associated tracks each having  $p_T > 500$  MeV. In events with multiple vertices, the one with the highest sum of squared transverse momenta of associated tracks is chosen as the primary vertex [62]. A set of baseline quality criteria are applied to reject events with non-collision backgrounds or detector noise [63].

Two levels of object identification requirements are defined for leptons and jets: baseline and signal. Baseline leptons and jets are selected with looser identification criteria, and are used in computing the missing transverse momentum as well as in resolving possible reconstruction ambiguities. Signal leptons and jets are a subset of the baseline objects, with tighter quality requirements which are used to define the search regions. Isolation criteria, defined with a list of tracking-based and calorimeter-based variables, are used to select signal leptons by discriminating between semileptonic heavy-flavour decays and jets misidentified as leptons.

Electron candidates are reconstructed from energy deposits in the electromagnetic calorimeter that are matched to charged-particle tracks in the inner detector (ID) [64]. Baseline electrons are required to satisfy  $p_T > 10$  GeV and  $|\eta| < 2.47$ , excluding the transition region between the barrel and endcap calorimeters ( $1.37 < |\eta| < 1.52$ ). They are identified using the ‘loose’ likelihood identification operating point as described in Ref. [64]. The number of hits in the innermost pixel layer is used to discriminate between electrons and converted photons. The longitudinal impact parameter  $z_0$  relative to the primary vertex is required to satisfy  $|z_0 \sin \theta| < 0.5$  mm. Signal electrons are required to also satisfy  $p_T > 20$  GeV and the ‘tight’ likelihood identification criteria as defined in Ref. [64]. The significance of the transverse impact parameter  $d_0$  must satisfy  $|d_0/\sigma(d_0)| < 5$  for signal electrons. Signal electrons with  $p_T < 200$  GeV are further refined using the ‘FCLoose’ isolation working point, while those with larger  $p_T$  are required to pass the ‘FCHigh-

PtCaloOnly’ isolation working point, as described in Ref. [64]. Corrections for energy contributions due to pile-up are applied.

Muon candidates are reconstructed from matching tracks in the ID and muon spectrometer, refined through a global fit which uses the hits from both subdetectors [65]. Baseline muons must have  $p_T > 10$  GeV and  $|\eta| < 2.5$ , and satisfy the ‘medium’ identification criteria. Like the electrons, their longitudinal impact parameter  $z_0$  relative to the primary vertex is required to satisfy  $|z_0 \sin \theta| < 0.5$  mm. Signal muons are defined with tighter requirements on their transverse momentum and transverse impact parameter significance:  $p_T > 20$  GeV and  $|d_0/\sigma(d_0)| < 3$ . The ‘FCLoose’ isolation working point is also required for signal muons [65].

Jets are reconstructed from topological clusters of energy depositions in the calorimeters using the anti- $k_r$  algorithm [66], with a radius parameter  $R = 0.4$  [67]. The average energy contribution from pile-up is subtracted according to the jet area and the jets are calibrated as described in Ref. [68]. To further reduce the effect of pile-up interactions, the jets with  $|\eta| < 2.4$  and  $p_T < 120$  GeV are required to satisfy the ‘medium’ working point of the jet vertex tagger (JVT), a tagging algorithm that identifies jets originating from the primary vertex using track information [69, 70]. Baseline jets are selected in the region  $|\eta| < 4.5$  and have  $p_T > 20$  GeV. The selection of signal jets requires them to be in the region  $|\eta| < 2.5$  and to have  $p_T > 30$  GeV.

Jets containing  $b$ -hadrons are identified as arising from  $b$ -quarks (‘ $b$ -tagged’) using a multivariate algorithm (MV2c10), based on the track impact parameters, the presence of displaced secondary vertices and the reconstructed flight path of  $b$ - and  $c$ -hadrons inside the jet [71]. These  $b$ -tagged jets are reconstructed in the region  $|\eta| < 2.5$  and have  $p_T > 20$  GeV. The  $b$ -tagging working point provides an efficiency of 77% for jets containing  $b$ -hadrons in simulated  $t\bar{t}$  events, with average rejection of 110 and 4.9 for light-flavour jets and jets containing  $c$ -hadrons, respectively [72].

To resolve the reconstruction ambiguities between electrons, muons and jets, an overlap removal procedure is applied to baseline objects in a prioritised sequence as follows. First, if an electron shares the same ID track with another electron, the one with lower  $p_T$  is discarded. Any electron sharing the same ID track with a muon is rejected. Next, jets that are not  $b$ -tagged are rejected if they lie within  $\Delta R = 0.2$  of an electron. Similarly, jets that are not  $b$ -tagged are rejected if they lie within  $\Delta R = 0.2$  of a muon if the jet has fewer than three associated tracks or the muon is matched to the jet through ghost association [73]. Finally, electrons and muons that are close to a remaining jet are discarded if their distance from the jet is  $\Delta R < \min(0.4, 0.04 + 10 \text{ GeV}/p_T)$  as a function of the lepton  $p_T$ .

The missing transverse momentum  $\vec{p}_T^{\text{miss}}$ , with magnitude  $E_T^{\text{miss}}$ , is calculated as the negative vectorial sum of the transverse momentum of all baseline reconstructed objects (electrons, muons, jets and photons [74]) and the soft term. The soft term includes all tracks associated with the primary vertex but not matched to any reconstructed physics object. Tracks not associated with the primary vertex are not considered in the  $E_T^{\text{miss}}$  calculation, improving the  $E_T^{\text{miss}}$  resolution by suppressing the effect of pile-up [75, 76].

To compensate for differences between data and simulation in trigger, particle identification and reconstruction efficiency, correction factors that are usually functions of the relevant kinematic variables are derived from data and applied to the samples of simulated events.

## 5 Analysis strategy

The search is conducted in three independent analysis channels differing in lepton and jet multiplicities to maximise the sensitivity to distinct signal processes. The  $tW_{1L}$  analysis channel targets  $tW$ +DM events where one of the  $W$  bosons (directly produced or arising from the top quark decay) decays leptonically (Sect. 5.2). The  $tW_{2L}$  analysis channel targets the same signal processes, but considers events where both  $W$  bosons decay leptonically (Sect. 5.3). The two selections are designed to be mutually exclusive. The results of these two analysis channels are statistically combined to maximise the sensitivity to the  $tW$ +DM processes. Finally, the  $tj_{1L}$  analysis targets  $t$ -channel production of DM candidates and requires a single lepton in each event (Sect. 5.4). In all analysis channels, large missing transverse momentum and jets are required. Event selections and background estimation methods specific to each analysis channel are described in this section, as are the definitions of the signal, control, and validation regions (SR, CR, and VR, respectively).

Dedicated CRs are designed in each analysis channel for the major SM background processes in order to predict their expected contribution in the SRs. The CRs and SRs are mutually exclusive, with the CRs enriched in the major background processes relevant to each analysis channel while minimising the contamination from signal. The potential signal contamination in the CRs is found to be negligible, at the level of  $< 3\%$  of the total SM expectation for all analysis channels.

The expected SM backgrounds are first determined independently for each channel, with a profile likelihood fit [77] in a background-only fit. In this fit, normalisation factors of the backgrounds, for which dedicated CRs are defined, are adjusted simultaneously to match the data in the associated CRs. The input to the background-only fit includes the number of events observed in the associated CRs and the number of events predicted by simulation in each CR for all background processes. They are both described by Poisson statistics. The systematic uncertainties, described in Sect. 6, are included in the fit as nuisance parameters. They are constrained by Gaussian distributions with widths corresponding to the sizes of the uncertainties and are treated as correlated, when appropriate, between the various regions. The product of the various probability density functions forms the likelihood, which the fit maximises by adjusting the background normalisation and the nuisance parameters.

Normalisation and nuisance parameters obtained from the background-only fit to the control regions are then extrapolated [77] to the SRs to quantify potential excess in data. The reliability of the MC extrapolation of the SM background estimates outside of the control regions is verified in dedicated validation regions. Statistically independent from the corresponding CRs and SRs, these VRs are designed to probe a kinematic region closer to that of the SRs. The potential signal contamination in the VRs is at the level of  $< 1\%$  of the total SM expectation for most validation regions, and between 8% and 15% in a few validation regions in the  $tW_{1L}$  analysis channel.

In the absence of a significant event excess in the SRs, as determined after the background-only fit, simultaneous fits of the CRs and SRs are performed to constrain the parameters of the targeted signal models as well as a generic beyond the standard model (BSM), referred to as model-dependent and model-independent signal fits as detailed in Sect. 7.

### 5.1 Kinematic requirements and event variables

The event selection criteria in each analysis channel are defined using the physics objects described in Sect. 4 and the event variables defined in this section.

The following variables are defined using simple combinations of the physics objects in the events.

- $N_{\text{jet}}$  is the number of jets with  $|\eta| < 2.5$  and  $p_T > 30$  GeV.
- $N_{\text{jet}}^{\text{forward}}$  is the number of jets in the forward region,  $2.5 < |\eta| < 4.5$  and  $p_T > 30$  GeV.
- $N_{b\text{-jet}}$  is the number of  $b$ -jets with  $|\eta| < 2.5$  and  $p_T$  above a given threshold defined in each analysis channel.
- The minimum azimuthal distance  $\Delta\phi_{\text{min}}$  between the  $\vec{p}_T^{\text{miss}}$  and the  $\vec{p}_T$  of each of the four leading jets in the event is useful for rejecting events with mismeasured jet energies leading to  $E_T^{\text{miss}}$  in the event, and is defined as:

$$\Delta\phi_{\text{min}} = \min_{i \leq 4} \Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_{T,i}^{\text{jet}}),$$

where  $\min_{i \leq 4}$  selects the jet that minimises  $\Delta\phi$ .

- $m_{\ell\ell}$  is the invariant mass of the dilepton system in the event.
- An iterative reclustering approach as defined in Ref. [78] is used to reconstruct the hadronically decaying  $W$  bosons. All the signal jets in the event are first reclustered using the anti- $k_r$  algorithm with a large radius parameter of  $R = 3.0$ . The radius of each large-radius jet is then iteratively reduced to an optimal radius,  $R(p_T) = 2 \times m_W / p_T$ . The mass of the reclustered jet,  $m_W^{\text{reclustered}}$ , is used in the  $tW_{1L}$  channel.
- $m_{\ell_1 b_1}$  is the invariant mass of the leading lepton and  $b$ -jet in the event.

A set of variables based on transverse mass are defined in order to distinguish between the signal and SM background processes in the following.

- The transverse mass formed by the  $\vec{p}_T^{\text{miss}}$  and the leading lepton in the event,  $m_T^{\text{lep}}$ , is used to reduce the  $W$ +jets and semileptonic  $t\bar{t}$  backgrounds. It is defined as:

$$m_T^{\text{lep}} = \sqrt{2p_T^\ell E_T^{\text{miss}} (1 - \cos \Delta\phi(\vec{p}_T^\ell, \vec{p}_T^{\text{miss}}))}.$$

- Similarly, the transverse mass  $m_T^{\ell b}$  is formed by the  $\vec{p}_T^{\text{miss}}$  and the system of the leading lepton and  $b$ -jet in the event to suppress the  $W + b$  background, and is defined as:

$$m_T^{\ell b} = \sqrt{2p_T^{\ell_1+b_1} E_T^{\text{miss}} (1 - \cos \Delta\phi(\vec{p}_T^{\ell_1+b_1}, \vec{p}_T^{\text{miss}}))}.$$

- Closely related to  $m_T^{\text{lep}}$ , the transverse mass  $m_{T2}$  [79, 80] is used to bound the masses of pair-produced particles, such as in  $t\bar{t}$  production, each of which decays so as to produce a visible particle that can be detected and an invisible particle that contributes to the missing transverse momentum. In the case of a dilepton final state, it

is defined by:

$$m_{T2}(\vec{p}_T^{\ell_1}, \vec{p}_T^{\ell_2}, \vec{p}_T^{\text{miss}}) = \min_{\vec{q}_T} \left[ \max \left( m_T^{\text{lep}}(\vec{p}_T^{\ell_1}, \vec{q}_T), m_T^{\text{lep}}(\vec{p}_T^{\ell_2}, \vec{p}_T^{\text{miss}} - \vec{q}_T) \right) \right],$$

where  $\vec{q}_T$  is the transverse momentum vector that minimises the larger of the two transverse masses  $m_T^{\text{lep}}$ , and  $\vec{p}_T^{\ell_1}$  and  $\vec{p}_T^{\ell_2}$  are the leading and subleading transverse momenta of the two leptons in the pair. For the dileptonic  $t\bar{t}$  background events,  $m_{T2}$  has a kinematic endpoint at  $m_W$ .

- The asymmetric transverse mass  $am_{T2}$  [81, 82], a variation of  $m_{T2}$ , is used in the  $tW_{1L}$  final state to reduce the number of dileptonic  $t\bar{t}$  background events where one of the leptons is undetected. For these events,  $am_{T2}$  has a kinematic endpoint at the top quark mass.

To improve the selection of single-top events in the  $tW_{2L}$  channel, the following quantities based on invariant mass are defined.

- $m_{b\ell}^{\text{min}}$  is the minimum invariant mass found by combining the leading  $b$ -jet with each of the leptons,  $m_{b\ell}^{\text{min}} = \min(m_{b_1\ell_1}, m_{b_1\ell_2})$ . An upper endpoint at approximately 153 GeV or 160–170 GeV is expected for the events with one or two leptonic top quark decays, respectively.
- To further reduce the background with two leptonic top quark decays, such as  $t\bar{t}$  and  $t\bar{t}V$ ,  $m_{b\ell}^t$ , an extended variation of  $m_{b\ell}^{\text{min}}$ , is used in the  $tW_{2L}$  final state. It is defined as:

$$m_{b\ell}^t = \min[\max(m_{\ell_1 j_1}, m_{\ell_2 j_2}), \max(m_{\ell_1 j_2}, m_{\ell_2 j_1})],$$

where  $m_{\ell_n j_m}$  is the invariant mass of lepton  $\ell_n$  and jet  $j_m$ , where  $j_1$  and  $j_2$  are the two jets with highest  $b$ -tag discriminator value. For the  $t\bar{t}$  and  $t\bar{t}V$  backgrounds where both top quarks decay leptonically,  $m_{b\ell}^t$  has a kinematic endpoint at approximately 160–170 GeV.

Additional variables based on angular separations of the objects are used in the  $tj_{1L}$  analysis to suppress SM background contributions, as defined below.

- $\Delta\eta(\ell_1, b_1)$ ,  $\Delta\phi(\ell_1, b_1)$ , and  $\Delta R(\ell_1, b_1)$ : the pseudorapidity difference, azimuthal angle difference, and angular distance between the leading lepton and  $b$ -jet in the event.
- $\Delta\phi(\ell_1, \vec{p}_T^{\text{miss}})$ : the azimuthal angle difference between the  $\vec{p}_T^{\text{miss}}$  and the leading lepton in the event.

Table 2 summarises the trigger and preselection requirements for all analysis channels, in terms of lepton, jet and

**Table 2** Summary of the trigger and preselection requirements for the three analysis channels. Opposite-sign leptons are indicated as (OS). Events with extra baseline leptons are vetoed in addition

Variable	tW <sub>1L</sub>	tW <sub>2L</sub>	tj <sub>1L</sub>
Trigger	$E_T^{\text{miss}}$	Dilepton	$E_T^{\text{miss}}$ OR one-lepton
$N_\ell^{\text{signal}}$	= 1	= 2 (OS)	= 1
$p_T(\ell_1)$ (GeV)	> 30	> 25	> 30
$p_T(\ell_2)$ (GeV)	–	> 20	–
$N_{\text{jet}}$	≥ 3	≥ 1	∈ [1, 4]
$p_T(\text{jet})$ (GeV)	> 30	> 30	> 30
$N_{b\text{-jet}}$	≥ 1	≥ 1	∈ [1, 2]
$p_T(b_1)$ (GeV)	> 50	> 50	> 50
$E_T^{\text{miss}}$ (GeV)	> 250	> 200	> 200
$m_T^{\text{lep}}$ (GeV)	> 30	–	> 60
$m_{\ell\ell}$ (GeV)	–	≥ 40, ∉ [71, 111] ( $ee/\mu\mu$ )	–
$\Delta\phi_{\text{min}}$ (rad)	> 0.5	–	> 0.5

$b$ -jet multiplicities, as well as transverse momenta and global kinematic variables. Events with extra baseline leptons are vetoed in addition.

### 5.2 Single-lepton tW<sub>1L</sub> analysis channel

Events with exactly one electron or muon are first selected for the SR if they also contain at least three jets, exactly one of which must be  $b$ -tagged, and satisfy the preselection requirements described in Table 2. The dominant SM background contributions in the channel are  $t\bar{t}$ ,  $W$ +jets, and single top ( $Wt$  channel) production. Discriminating variables,  $E_T^{\text{miss}}$ ,  $m_T^{\text{lep}}$ ,  $m_W^{\text{reclustered}}$  and the asymmetric transverse mass  $am_{T2}$  as described in Sect. 5.1, are used to further separate the signal from backgrounds. A ‘genetic algorithm’ [83] is used to optimise a baseline signal region defined as in Table 3. To increase the sensitivity to different signal model parameters, a binned  $E_T^{\text{miss}}$  distribution is used as the final input for the statistical analysis. The binning is chosen to be [250, 300] GeV, [300, 400] GeV, [400, 500] GeV, [500, 600] GeV and  $\geq 600$  GeV, referred to as Bins [0–4].

The acceptance times detector efficiency for the  $tW$ +DM signal processes after applying all selection criteria is between 0.3% and 5.1% in the parameter space of  $\tan\beta = 1$ ,  $m_a \in [100, 450]$  GeV and  $m_{H^\pm} \in [400, 1500]$  GeV, and between 0.2% and 4.8% in the parameter space of  $m_a = 250$  GeV,  $\tan\beta \in [0.5, 30]$  and  $m_{H^\pm} \in [400, 1500]$  GeV.

Dominant background contributions from the  $t\bar{t}$  and  $W$ +jets processes are estimated using MC simulation and the dedicated CRs. The contribution from multijet production, where the lepton is a misidentified jet or originates from a heavy-flavour hadron decay or photon conversion, is found to be negligible. The remaining sources of background (single-top,  $Z$ +jets, diboson,  $t\bar{t}V$ , and  $tWZ$  production, as well as rarer processes such as triboson,  $t\bar{t}\bar{t}$ , and  $t\bar{t}WW$ ), are estimated from simulation.

Dedicated control regions CR<sub>tW<sub>1L</sub>( $t\bar{t}$ )</sub> and CR<sub>tW<sub>1L</sub>( $W$ )</sub>, defined in Table 3, are designed for the  $t\bar{t}$  and  $W$ +jets background estimations. Compared to the SR, the acceptance for  $t\bar{t}$  events is increased in CR<sub>tW<sub>1L</sub>( $t\bar{t}$ )</sub> by requiring at least two  $b$ -jets, inverting the selection on  $am_{T2}$  and removing the requirement on  $m_W^{\text{reclustered}}$ . To increase the acceptance of the  $W$ +jets events and hence the sample size, CR<sub>tW<sub>1L</sub>( $W$ )</sub> is first selected by requiring  $40 < m_T^{\text{lep}} < 100$  GeV and  $m_W^{\text{reclustered}} < 60$  GeV. To exploit the lepton charge asymmetry of the  $W$ +jets events relative to the remaining backgrounds, it is subsequently split into two regions with opposite lepton charges, CR<sub>tW<sub>1L</sub>( $W^+$ )</sub> and CR<sub>tW<sub>1L</sub>( $W^-$ )</sub>. Normalisation factors,  $\mu_{t\bar{t}}$  and  $\mu_{W\text{+jets}}$ , defined as the ratio of the number of observed events to the SM prediction, are found to be  $0.96 \pm 0.08$  and  $1.01 \pm 0.05$  after the background-only fit for the  $t\bar{t}$  and  $W$ +jets processes, respectively.

To validate the  $t\bar{t}$  background predictions and the reliability of MC extrapolation in  $m_W^{\text{reclustered}}$  and  $am_{T2}$ , two validation regions, VR1<sub>tW<sub>1L</sub>( $t\bar{t}$ )</sub> and VR2<sub>tW<sub>1L</sub>( $t\bar{t}$ )</sub>, are defined by reversing the SR selection requirements on  $am_{T2}$  and  $m_W^{\text{reclustered}}$  respectively, as shown in Table 3. To increase the sample size, the SR selection requirement on the  $m_W^{\text{reclustered}}$  is removed in the VR1<sub>tW<sub>1L</sub>( $t\bar{t}$ )</sub> region. Similarly, for the  $W$ +jets background processes, two validation regions, VR1<sub>tW<sub>1L</sub>( $W$ )</sub> and VR2<sub>tW<sub>1L</sub>( $W$ )</sub>, are defined by varying the SR selection requirements on  $m_T^{\text{lep}}$  and  $m_W^{\text{reclustered}}$  shown in Table 3, respectively. Each of the  $W$ +jets validation regions is split into two regions with opposite lepton charge. Figure 2 shows the post-fit  $E_T^{\text{miss}}$  distributions in the representative validation regions. Good agreement is observed between data and SM expectation in all validation regions. The observed yield, post-fit background estimates and significance [84] in each CR and VR are shown in Fig. 3 after the background-only fit. Since the  $W$ +jets CR is split into two regions with opposite lepton charges sharing the same normalisation factor, the

**Table 3** Summary of signal, control and validation region definitions used in the  $tW_{1L}$  analysis channel. The ‘-’ entries represent an inclusive selection with no requirements. The  $W$ +jets control and validation

regions are each split into two regions with opposite lepton charges as described in the text

Variable	SR	CR( $t\bar{t}$ )	CR( $W$ )	VR1( $t\bar{t}$ )	VR2( $t\bar{t}$ )	VR1( $W$ )	VR2( $W$ )
$N_{b\text{-jet}}$	= 1	$\geq 2$	= 1	= 1	= 1	= 1	= 1
$p_T(b_2)$ [GeV]	< 50	> 50	< 50	< 50	< 50	< 50	< 50
$m_W^{\text{reclustered}}$ [GeV]	> 60	-	< 60	-	< 60	> 60	< 60
$m_T^{\text{lep}}$ [GeV]	> 200	> 200	$\in [40, 100]$	> 200	> 200	$\in [40, 100]$	> 100
$am_{T2}$ [GeV]	> 220	< 220	> 220	< 220	> 220	> 220	> 220

significances in the CRs are shown explicitly. The data event yields are found to be consistent with background expectations.

### 5.3 Dilepton $tW_{2L}$ analysis channel

Events with exactly two oppositely charged leptons (electron or muon) are first selected for the SR if they also contain at least one signal jet, at least one of which must be  $b$ -tagged with  $p_T > 50$  GeV, and satisfy the preselection requirements described in Table 2. The dominant SM background contributions in the channel after these selections are from the  $t\bar{t}$ ,  $t\bar{t}Z$ , and  $tWZ$  processes, followed by that of diboson events. The contribution from misidentified or non-prompt lepton backgrounds (referred to as ‘Fakes /non-prompt’ in Figs. 4 and 5) is found to be negligible in the signal region.

Discriminating variables,  $m_{b\ell}^{\text{min}}$ ,  $m_{b\ell}^t$ ,  $m_{T2}$  and  $\Delta\phi_{\text{min}}$  as defined in Sect. 5.1, are used to define the final signal region as shown in Table 4.

The acceptance times detector efficiency after applying all selection criteria for the  $tW$ +DM signal processes is between 0.07% and 0.7% in the parameter space of  $\tan\beta = 1$ ,  $m_a \in [100, 450]$  GeV and  $m_{H^\pm} \in [400, 1500]$  GeV, and between 0.05% and 0.6% in the parameter space of  $m_a = 250$  GeV,  $\tan\beta \in [0.5, 30]$  and  $m_{H^\pm} \in [400, 1500]$  GeV.

The contributions from the  $t\bar{t}$ ,  $t\bar{t}V$  (with  $V = W$  or  $Z$  boson) and diboson background processes are estimated from MC simulation and dedicated CRs. The remaining sources of background, including the irreducible  $tWZ$  process, which is dominated by the  $Z \rightarrow \nu\nu$  component, single top quark production,  $t\bar{t}h$  production and other rarer processes such as  $t\bar{t}t\bar{t}$  and  $t\bar{t}WW$ , are estimated from simulation.

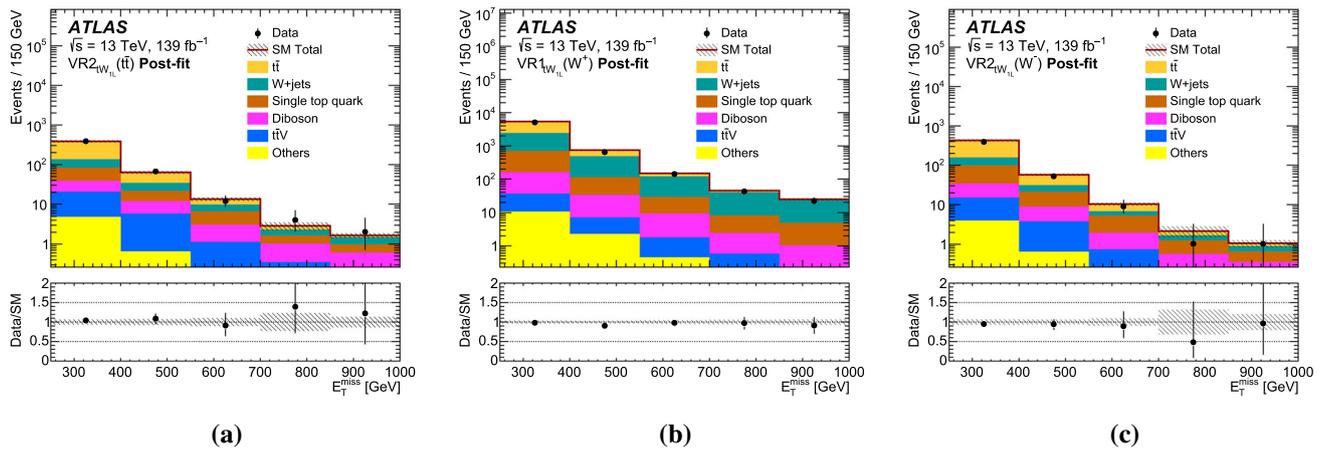
The acceptance for  $t\bar{t}$  events is increased in  $\text{CR}_{tW_{2L}}(t\bar{t})$  by requiring a low value of  $m_{T2}$  and inverting the SR selection criteria on  $m_{b\ell}^t$ .

The  $t\bar{t}V$  contribution is dominated by the  $t\bar{t}Z$  component (about 80% of  $t\bar{t}V$  in the SR), especially where  $Z \rightarrow \nu\nu$ . A dedicated control region,  $\text{CR}_{tW_{2L}}(t\bar{t}Z)$ , is defined by first selecting three leptons, where at least one same-flavour–opposite-charge (SFOS) pair is required to be consistent with coming from a  $Z$  boson decay with an invariant mass within

a window of [71, 111] GeV. If more than one such pair is present in the event, the pair which has an invariant mass closest to the  $Z$  boson mass is chosen. The purity of  $t\bar{t}Z$  events is further increased by requiring at least three jets. To reduce the diboson background in this region, events with exactly one  $b$ -jet and three jets are rejected.

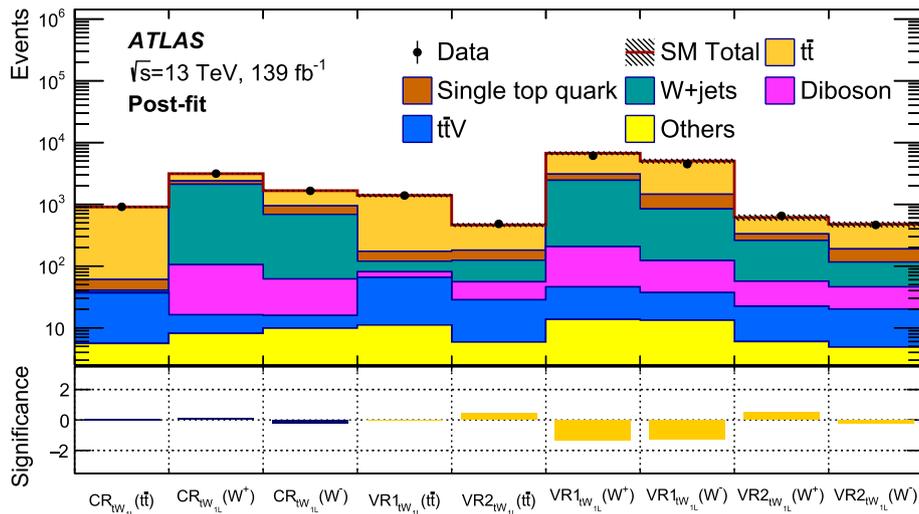
Due to the presence of three leptons in this region, the background contribution from misidentified or non-prompt leptons becomes non-negligible and is estimated using a data-driven matrix method (MM) as described in Refs. [85, 86]. Two types of lepton identification criteria, ‘tight’ and ‘loose’ are defined in the evaluation, corresponding to the baseline and signal lepton selections described in Sect. 4. The number of events containing misidentified or non-prompt leptons in the  $t\bar{t}Z$  CR is estimated from the number of observed events with tight or loose leptons using as input the probability for loose prompt, misidentified or non-prompt leptons to satisfy the tight criteria. The probability for prompt loose leptons to pass the tight selection is determined from  $t\bar{t}Z$  MC simulation. The equivalent probability for loose misidentified or non-prompt leptons to pass the tight selection is measured in a  $t\bar{t}$ -enriched region with two same-sign leptons (electrons or muons) and a least one  $b$ -tagged jet, which is dominated by events with at least one misidentified or non-prompt lepton.

In the  $\text{CR}_{tW_{2L}}(t\bar{t}Z)$  region, to mimic the event topology of the  $t\bar{t}Z$  background in the signal region, a corrected  $\vec{p}_T^{\text{miss}}$  is obtained by vectorially adding the transverse momenta of the SFOS pair, and it is subsequently used to calculate a transverse mass ( $m_T^{\text{lep}}$ ) with the third lepton, referred to as corrected  $m_{T2}$ . The two leptons from the SFOS pair are excluded in the calculation of  $m_{b\ell}^{\text{min}}$ , which effectively becomes the invariant mass of the third lepton and the leading  $b$ -jet. To improve the estimation of the dominant background from the  $WZ$  process in the  $\text{CR}_{tW_{2L}}(t\bar{t}Z)$ , a dedicated  $WZ$  CR,  $\text{CR}_{tW_{2L}}(WZ)$ , is defined by inverting the  $\text{CR}_{tW_{2L}}(t\bar{t}Z)$  selection requirements on the jet multiplicity and the corrected  $m_{b\ell}^{\text{min}}$ . This CR is also used to aid in the estimation of all diboson processes in the SR. Normalisation factors  $\mu_{t\bar{t}}$ ,  $\mu_{t\bar{t}V}$  and  $\mu_{\text{Diboson}}$  are found to be  $1.00 \pm 0.03$ ,  $0.76 \pm 0.26$  and  $0.80 \pm 0.16$  after the background-only fit for the  $t\bar{t}$ ,  $t\bar{t}V$  and diboson processes, respectively.



**Fig. 2** The  $E_T^{\text{miss}}$  distributions after the background-only fit (post-fit) are shown in three representative validation regions: **a**  $\text{VR}2_{tW_{1L}}(\bar{t}t)$ , **b**  $\text{VR}1_{tW_{1L}}(W^+)$  and **c**  $\text{VR}2_{tW_{1L}}(W^-)$ . The uncertainty bands plotted include all statistical and systematic uncertainties. The ‘Others’ category includes contributions from  $Z$ +jets and  $tWZ$  production, and rare

processes such as triboson,  $t\bar{t}\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. The overflow events, where present, are included in the last bin. The lower panels show the ratio of data to the background prediction. The hatched error bands indicate the combined experimental and MC statistical uncertainties on these background predictions



**Fig. 3** Comparison of the predicted backgrounds with the observed numbers of events in the CRs and VRs associated with the  $tW_{1L}$  channel. The normalisation of the backgrounds is obtained from the background-only fit to the CRs. The ‘Others’ category includes contributions from  $Z$ +jets and  $tWZ$  production, and rare processes such as triboson,  $t\bar{t}\bar{t}$ ,

$t\bar{t}WW$ , and Higgs boson production processes. The upper panel shows the observed number of events and the predicted background yield. All uncertainties are included in the uncertainty band. The lower panel shows the significances in each region

A validation region,  $\text{VR}_{tW_{2L}}(\bar{t}t)$ , is defined in order to validate the  $t\bar{t}$  background predictions by applying all the signal selection criteria, apart from requiring lower values of  $m_{T2}$ , as shown in Table 4. For the background predictions of the  $t\bar{t}V$  and diboson processes, a  $3\ell$  validation region,  $\text{VR}_{tW_{2L}}(3L)$ , is defined with selection requirements similar to those of the  $\text{CR}_{tW_{2L}}(\bar{t}tZ)$  and  $\text{CR}_{tW_{2L}}(WZ)$ . To ensure that the  $\text{VR}_{tW_{2L}}(3L)$  is orthogonal to those two CRs, the selection on the corrected  $m_{b\ell}^{\text{min}}$  variable is varied according to the jet and  $b$ -jet multiplicities. For the events with exactly one  $b$ -jet,

the corrected  $m_{b\ell}^{\text{min}}$  is required to be larger than 170 GeV if  $N_{\text{jet}} > 3$ , or smaller than 170 GeV if  $N_{\text{jet}} \leq 3$ . For the events with more than one  $b$ -jet and  $N_{\text{jet}} > 2$ , the corrected  $m_{b\ell}^{\text{min}}$  is required to be larger than 170 GeV. To increase the sample size in this region, the  $p_T$  threshold for the  $b$ -tagged jets is reduced to 40 GeV.

Figure 4 shows the post-fit kinematic distributions in the validation regions. Good agreement is observed between data and the SM expectation in all validation regions. The observed yield, post-fit background estimates and signifi-

cance [84] in each CR and VR are shown in Fig. 5 after the background-only fit. The data event yields are found to be consistent with background expectations.

#### 5.4 Single-lepton $t_{j_{1L}}$ analysis channel

Events with exactly one electron or muon are first selected for the SR if they also contain 1–4 jets with  $p_T > 30$  GeV, one or two of which must be  $b$ -tagged, and satisfy the preselection requirements described in Table 2. The fourth jet in the event, if present, is required to have  $p_T < 50$  GeV. The second  $b$ -tagged jet is required to have  $p_T > 30$  GeV. The dominant SM background contributions in this channel are from  $t\bar{t}$ ,  $W$ +jets, and single top ( $Wt$  channel) production. Discriminating variables,  $E_T^{\text{miss}}$ ,  $m_T^{\text{lep}}$ ,  $N_{\text{jet}}^{\text{forward}}$  and  $\Delta\phi(\ell_1, b_1)$  as described in Sect. 5.1, are used to define the signal region as shown in Table 5.

To further improve the sensitivity, a boosted decision tree (BDT), provided by the Toolkit for Multivariate Analysis (TMVA) [87], is trained to distinguish between signal and background processes, using events passing the preselection defined in Table 2. BDT training settings found to be optimal for this analysis include number of trees set to 1500 with a maximum depth of 5 and gradient boosting. Cross-validation is performed to ensure there is no over-training. The following nine kinematic variables defined in Sect. 5.1 are used as input:

- $p_T$  and  $\eta$  of the highest- $p_T$  jet:  $p_T(j_1)$  and  $\eta(j_1)$ .
- The transverse masses:  $m_T^{\text{lep}}$  and  $m_T^{\ell b}$ .
- $\eta^{\ell b}$  of the leading lepton and  $b$ -jet system.
- The invariant mass of, and angular distances between, the highest- $p_T$  lepton and  $b$ -jet:  $m_{\ell_1 b_1}$ ,  $\Delta\phi(\ell_1, b_1)$ , and  $\Delta R(\ell_1, b_1)$ .
- The azimuthal separation between the highest- $p_T$  lepton and missing transverse momentum,  $\Delta\phi(\ell_1, \vec{p}_T^{\text{miss}})$ .

To explore the kinematic features in different regions of the signal parameter space, samples with different signal model parameters are used as an ensemble in the training. A binned distribution of the BDT output score above 0.6 is then used to extract the final results in the signal regions. The binning of the distribution is optimised as [0.6, 0.75], [0.75, 0.85], [0.85, 0.9] and [0.9, 1.0], referred to as Bins [0–3].

The acceptance times detector efficiency after applying all selection criteria for  $t$ -channel production in the signal models is between 0.37% (0.36%) and 0.73% (0.67%) in the parameter space of  $m_a = 250$  GeV,  $\tan\beta = 0.3$  (0.5) and  $m_{H^\pm} \in [500, 1750]$  GeV.

Similarly to the  $tW_{1L}$  analysis channel, dominant backgrounds from the  $t\bar{t}$  and  $W$ +jets processes are estimated using MC simulation and dedicated CRs. The contribution from

multijet production is found to be negligible. The remaining sources of background (single-top,  $Z$ +jets, diboson,  $t\bar{t}V$ ,  $t\bar{t}h$ ,  $tWZ$  production and rarer processes such as triboson,  $t\bar{t}t\bar{t}$ , and  $t\bar{t}WW$ ) are estimated from simulation.

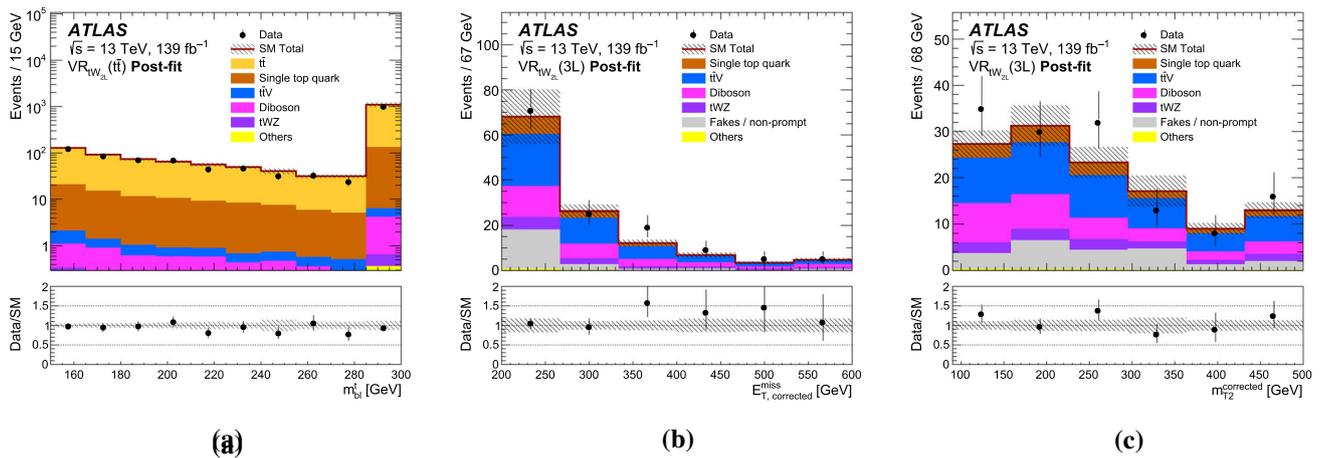
Dedicated control regions  $\text{CR}_{t_{j_{1L}}}(\bar{t}\bar{t})$  and  $\text{CR}_{t_{j_{1L}}}(W)$  are designed to estimate the  $t\bar{t}$  and  $W$ +jets background processes, respectively, as shown in Table 5. Compared to the SR, the acceptance for  $t\bar{t}$  events is increased in  $\text{CR}_{t_{j_{1L}}}(\bar{t}\bar{t})$  by requiring exactly two  $b$ -jets and large  $\Delta\phi(\ell_1, b_1)$  values. The contribution from  $W$ +jets events in the  $\text{CR}_{t_{j_{1L}}}(W)$  is enhanced by selecting events with one or two jets, exactly one  $b$ -jet, and low  $m_T^{\text{lep}}$  and large  $\Delta\phi(\ell_1, b_1)$  values. No splitting based on the  $W$  boson charge is applied. The normalisation factors  $\mu_{t\bar{t}}$  and  $\mu_{W+\text{jets}}$  are found to be  $1.00 \pm 0.27$  and  $1.10 \pm 0.13$  for the  $t\bar{t}$  and  $W$ +jets processes, respectively.

To validate the  $t\bar{t}$  background predictions, a validation region  $\text{VR}_{t_{j_{1L}}}(\bar{t}\bar{t})$  is defined by requiring a BDT score that is lower than in the SR definition, as shown in Table 5. For the  $W$ +jets background, a validation region  $\text{VR}_{t_{j_{1L}}}(W)$  is defined by requiring a lower  $m_T^{\text{lep}}$  value than in the SR definition, as shown in Table 5. To ensure orthogonality to the corresponding CRs, events in these two VRs are required to have low  $\Delta\phi(\ell_1, b_1)$ . Figure 6 shows the post-fit distribution of representative kinematic variables and the BDT score for these two validation regions. Good agreement is observed between data and expectation in all validation regions. The observed yield, post-fit background estimates and significance [84] in each CR and VR are shown in Fig. 7 after the background-only fit. The data event yields are found to be consistent with background expectations.

## 6 Systematic uncertainties

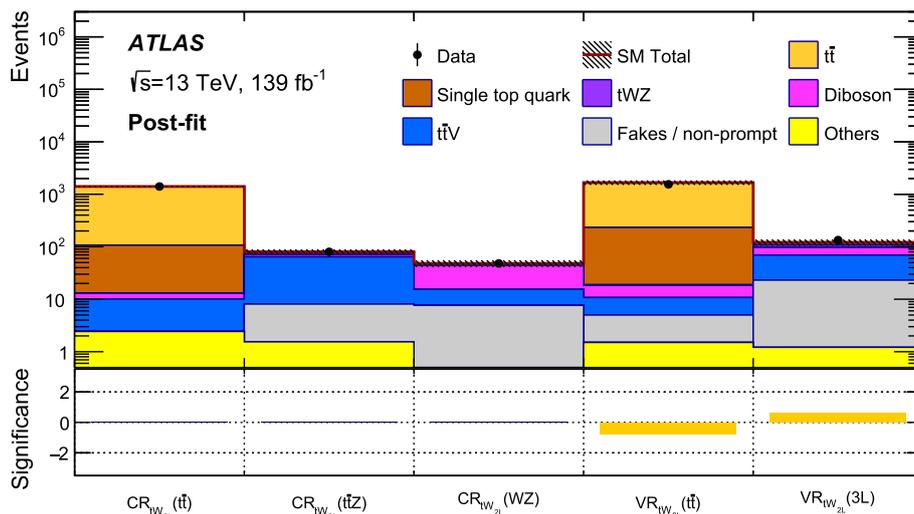
Several sources of experimental and theoretical systematic uncertainty in the signal and background estimates are considered. Their impact is reduced through the normalisation of the dominant backgrounds in the control regions defined with kinematic selections resembling those of the corresponding signal region. Uncertainties are included as nuisance parameters, common across all regions, with Gaussian constraints in the likelihood fits, taking into account correlations between different regions. Uncertainties due to the numbers of events in the CRs are also included in the fit for each region. The magnitude of the contributions arising from uncertainties on the background normalisation factors  $\mu$  and on the detector, theoretical modelling and statistics of the MC samples are summarised in Fig. 8 as a relative uncertainty in the total background yield for each SR in the three analysis channels.

Dominant detector-related systematic uncertainties arise from the jet energy scale and resolution, and from the  $b$ -tagging efficiency and mis-tagging rates.



**Fig. 4** The kinematic distributions in the  $t\bar{t}$  and  $3\ell$  validation regions of the  $tW_{2L}$  analysis channel after the background-only fit: **a**  $m_{bl}^t$  in  $VR_{tW_{2L}}(t\bar{t})$ , **b**  $E_T^{miss}$  in  $VR_{tW_{2L}}(3L)$  and **c**  $m_{T2}$  in  $VR_{tW_{2L}}(3L)$ . The uncertainty bands plotted include all statistical and systematic uncertainties. The ‘Others’ category includes contributions from rare processes such as triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}W$ , and Higgs boson production processes.

The overflow events, where present, are included in the last bin. Since the  $m_{bl}^t$  is defined for events with at least two jets, the events with exactly one jet are included in the overflow bin. The lower panels show the ratio of data to the background prediction. The hatched error bands indicate the combined experimental and MC statistical uncertainties on these background predictions



**Fig. 5** Comparison of the predicted backgrounds with the observed numbers of events in the CRs and VRs associated with the  $tW_{2L}$  channel. The normalisation of the backgrounds is obtained from the background-only fit to the CRs. The ‘Others’ category includes contributions from rare processes such as triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}W$ , and Higgs boson production processes.

The upper panel shows the observed number of events and the predicted background yield. All uncertainties are included in the uncertainty band. The lower panel shows the significances estimated for each region

The uncertainties in the jet energy scale and resolution are based on their respective measurements in data [68] and are derived as a function of the  $p_T$  and  $\eta$  of the jet, as well as of the pile-up conditions and the jet flavour composition (light-quark,  $b$ -quark, or gluon-initiated jets) of the selected jet sample. Their contributions to the SRs are the dominant experimental uncertainty components and are almost equivalent in all analysis channels. The systematic uncertainty in the  $b$ -tagging efficiency is the second largest experimental uncer-

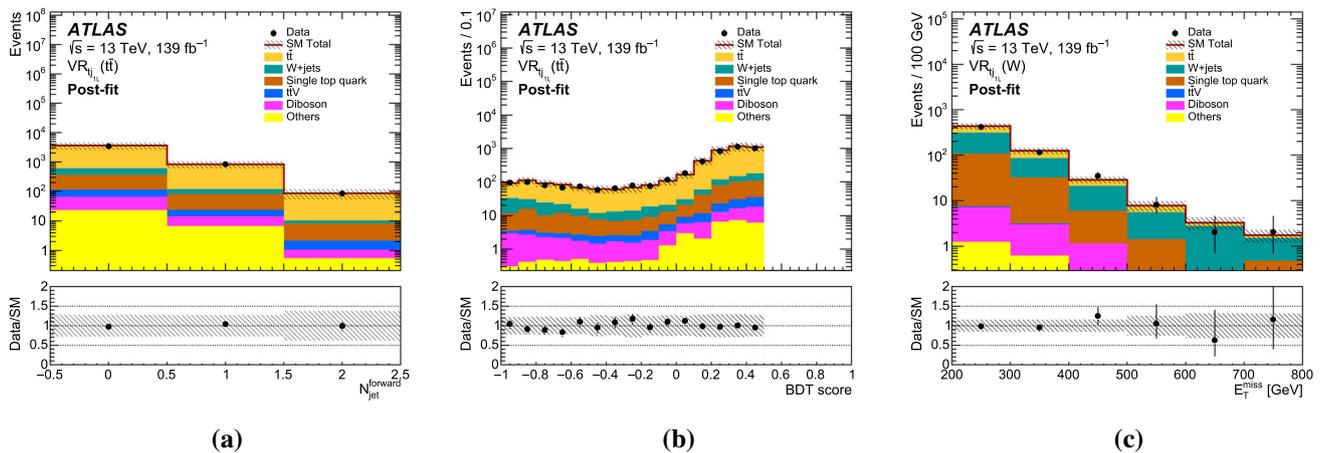
tainty. It ranges from 4.5% for  $b$ -jets with  $p_T \in [35, 40]$  GeV up to 7.5% for  $b$ -jets with high  $p_T$  ( $> 100$  GeV). The  $b$ -tagging uncertainty is estimated by varying the  $\eta$ -,  $p_T$ - and flavour-dependent scale factors applied to each jet in the simulation within a range that reflects the systematic uncertainty in the measured tagging efficiency and mis-tag rates in data [71]. The uncertainties associated with trigger requirements, pile-up modelling, and lepton reconstruction and energy measurements have a small or negligible impact on the final

**Table 4** Summary of signal, control and validation region definitions used in the  $tW_{2L}$  analysis channel. The ‘-’ entries represent an inclusive selection with no requirements. In the final states with three leptons, the corrected  $E_T^{\text{miss}}$ ,  $m_{b\ell}^{\text{min}}$  and  $m_{T2}$  variables are used instead as described

Variable	SR	CR( $t\bar{t}$ )	CR( $t\bar{t}Z$ )	CR(WZ)	VR( $t\bar{t}$ )	VR( $3\ell$ )
$N_\ell^{\text{signal}}$	= 2 (OS)	= 2 (OS)	= 3 (≥ 1 SFOS)	= 3 (≥ 1 SFOS)	= 2 (OS)	= 3 (≥ 1 SFOS)
$p_T(\ell_3)$ (GeV)	-	-	> 20	> 20	-	> 20
$m_{ee/\mu\mu}$ (GeV)	∉ [71, 111]	∉ [71, 111]	∈ [71, 111]	∈ [71, 111]	∉ [71, 111]	∈ [71, 111]
$N_{\text{jet}}$	≥ 1	≥ 1	≥ 3	∈ [1, 3]	≥ 1	≥ 1
$N_{b\text{-jet}}$	≥ 1	≥ 1	≥ 1 (≥ 2 if $N_{\text{jet}} = 3$ )	= 1	≥ 1	≥ 1
$m_{b\ell}^{\text{min}}$ (GeV)	< 170	< 170	< 170	> 170	< 170	varies
$m_{b\ell}^{\text{t}}$ (GeV)	> 150	< 150	-	-	> 150	-
$m_{T2}$ (GeV)	> 130	∈ [40, 80]	> 90	> 90	∈ [40, 80]	> 90
$\Delta\phi_{\text{min}}$ (rad)	> 1.1	> 1.1	-	-	> 1.1	-

**Table 5** Summary of signal, control and validation region definitions used in the  $tj_{1L}$  analysis channel. The ‘-’ entries represent an inclusive selection with no requirements

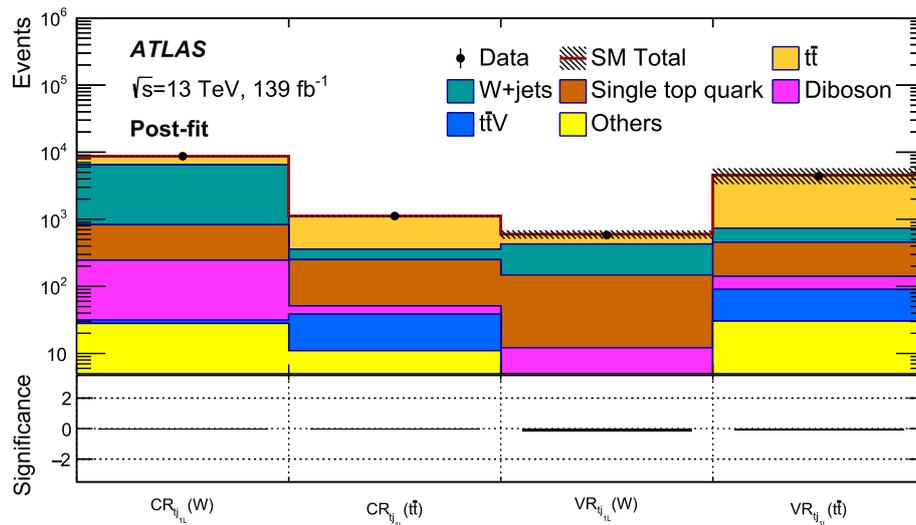
Variable	SR	CR( $t\bar{t}$ )	CR(W)	VR( $t\bar{t}$ )	VR(W)
$N_{\text{jet}}$	∈ [1, 4]	∈ [1, 4]	∈ [1, 2]	∈ [1, 4]	∈ [1, 2]
$N_{b\text{-jet}}$	∈ [1, 2]	= 2	= 1	∈ [1, 2]	= 1
$N_{\text{jet}}^{\text{forward}}$	> 0	-	-	-	-
$E_T^{\text{miss}}$ (GeV)	> 225	> 225	> 225	> 225	> 225
$m_T^{\text{lep}}$ (GeV)	> 100	> 100	∈ [60, 100]	> 100	∈ [60, 100]
$\Delta\phi(\ell_1, b_1)$ (rad)	< 1.2	> 1.5	> 1.5	< 1.5	< 1.5
BDT score	> 0.6	incl.	incl.	< 0.5	incl.



**Fig. 6** Distributions in the  $t\bar{t}$  and  $W$ +jets validation regions in the  $tj_{1L}$  analysis channel: **a**  $N_{\text{jet}}^{\text{forward}}$  in  $\text{VR}_{tj_{1L}}(t\bar{t})$ , **b** BDT score in  $\text{VR}_{tj_{1L}}(t\bar{t})$  and **c**  $E_T^{\text{miss}}$  in  $\text{VR}_{tj_{1L}}(W)$ . The normalisation of the backgrounds is obtained from the background-only fit to the CRs. The uncertainty bands plotted include all statistical and systematic uncertainties. The ‘Others’ cate-

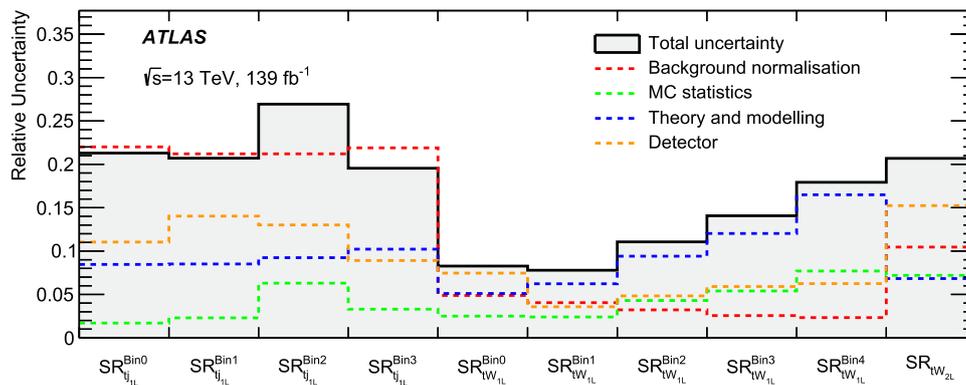
gory includes contributions from  $Z$ +jets and  $tWZ$  production, and rare processes such as triboson,  $t\bar{t}\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. The overflow events, where present, are included in the last bin. The lower panels show the ratio of data to the background prediction. The hatched error bands indicate the combined experimental and MC statistical uncertainties on these background predictions

gory includes contributions from  $Z$ +jets and  $tWZ$  production, and rare processes such as triboson,  $t\bar{t}\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. The overflow events, where present, are included in the last bin. The lower panels show the ratio of data to the background prediction. The hatched error bands indicate the combined experimental and MC statistical uncertainties on these background predictions



**Fig. 7** Comparison of the predicted backgrounds with the observed numbers of events in the CRs and VRs associated with the  $tj_{1L}$  channel. The normalisation of the backgrounds is obtained from the background-only fit to the CRs. The upper panel shows the observed number of events and the predicted background yield. The ‘Others’ category includes con-

tributions from  $Z$ +jets and  $tWZ$  production, and rare processes such as triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. All uncertainties are included in the uncertainty band. The lower panel shows the significance for each region



**Fig. 8** Relative uncertainties in the total background yield in each SR for the three analysis channels, including the contribution from the different sources of uncertainty. The ‘Detector’ category contains all detector-related systematic uncertainties and is dominated by the jet energy scale and resolution. The ‘Background normalisation’ repre-

sents the uncertainty in the fitted normalisation factors, including the available event counts in the CRs. Individual uncertainties can be correlated, and do not necessarily add up in quadrature to the total background uncertainty

results; however, the lepton, photon and jet-related uncertainties are propagated to the calculation of the  $E_T^{miss}$ , and additional uncertainties due to the energy scale and resolution of the soft term are included in the  $E_T^{miss}$ . Finally, uncertainties in estimates of the non-prompt or misidentified leptons background are found to be below 1% in the  $tW_{2L}$  analysis channel and negligible for single-lepton selections.

Uncertainties in the modelling of the SM background processes in MC simulation and their theoretical cross-section uncertainties are also taken into account. Furthermore, for these processes the 1.7% uncertainty in the combined 2015–2018 integrated luminosity is included.

Modelling uncertainties in the  $t\bar{t}$  and single-top backgrounds are dominant in all SRs for the  $tW_{1L}$  and  $tj_{1L}$  analysis channels, and the second leading source of uncertainty for the  $tW_{2L}$  SR. They are computed as the difference between the predictions from nominal samples and those from additional samples differing in hard-scattering generator and parameter settings, or by using internal weights assigned to the events depending on the choice of renormalisation and factorisation scales ( $\mu_R$  and  $\mu_F$ , respectively, varied independently by factors of 2 and 0.5), initial- and final-state radiation parameters, and PDF sets. The impact of the PS and hadronisation model is evaluated by comparing the nominal

generator with a POWHEG-BOX sample interfaced to HERWIG 7 [88, 89], using the H7UE set of tuned parameters [89]. To assess the uncertainty due to the choice of hard-scattering generator and matching scheme, an alternative generator setup using MADGRAPH5\_aMC@NLO interfaced to PYTHIA 8 is employed. For single-top  $Wt$  production, the impact of interference between single-resonant and double-resonant top quark production and on the implementation of the  $W$  lineshape in the generator is estimated in all analysis channels by comparing the nominal sample generated using the diagram removal method with alternative samples, including those generated using the diagram subtraction method [90]. For the  $tW_{2L}$  selection, this results in a 100% uncertainty in the subdominant  $Wt$  contribution.

For the  $t\bar{t} + W/Z$  background, uncertainties due to parton shower and hadronisation modelling are evaluated by comparing the predictions from MADGRAPH5\_aMC@NLO interfaced to PYTHIA 8 and HERWIG 7, while the uncertainties related to the choice of renormalisation and factorisation scales are assessed by varying the corresponding event generator parameters up and down by a factor of two around their nominal values. Their contribution is dominant in the  $tW_{2L}$  analysis channel and subdominant or small in all other SRs. A similar approach is used to assess the uncertainties in the  $tWZ$  process, with an additional 20% uncertainty assigned to account for uncertainties in the effects of interference between the  $t\bar{t} + W/Z$  and  $tWZ$  processes. The 20% is assigned on the basis of preliminary comparisons of alternative approaches developed to evaluate interference effects in the  $t\bar{t}-tW$  [91] and  $t\bar{t}Z-tWZ$  processes [92].

Finally, modelling and normalisation uncertainties in minor backgrounds are also considered. For diboson and  $W/Z$ +jets events, they are estimated by varying the renormalisation, factorisation and resummation scales up and down by a factor of two around the values used to generate the nominal samples. For  $t\bar{t}WW$ ,  $tZ$ ,  $t\bar{t}H$ ,  $Wh$ ,  $Zh$ ,  $t\bar{t}\bar{t}$ , and triboson production processes, experimental and theoretical uncertainties in the event yields are also evaluated and found to be negligible.

For the DM signal processes, both the experimental and theoretical uncertainties in the expected signal yields are considered, including the aforementioned luminosity uncertainty. Experimental uncertainties are found to be 3–35% (2.5–11%) across the  $m_a-m_{H^\pm}$  and  $m_a-\tan\beta$  planes for the  $tW_{1L}$  ( $tW_{2L}$ ) analysis channel, and in the range 3–14% as a function of  $m_{H^\pm}$  for the  $tj_{1L}$  selection, independently of  $\tan\beta$ . In all SRs, the dominant uncertainty in the signal yields is found to be from the jet energy scale and resolution, followed by uncertainties in  $b$ -tagging rates. Larger uncertainties for the  $tW_{1L}$  selections are found for the highest  $E_T^{\text{miss}}$ -binned region, where MC statistical fluctuations are also relevant. In the modelling of the signal samples, uncertainties due to the variations of the renormalisation and factorisa-

tion scales are dominant. They are evaluated using a variation scheme wherein  $\mu_R$  and  $\mu_F$  are scaled simultaneously by either a factor of 2 or 0.5. For the PS and hadronisation uncertainties, alternative samples with varied A14 tune parameter values are used. The effect of each systematic variation on the acceptance and efficiency is evaluated for each analysis channel SR by comparing the variation samples with the corresponding nominal sample. The impact on the total yields for  $tW+DM$ ,  $t\bar{t}+DM$  and  $t$ -channel production processes is also evaluated for each signal scenario and found to be between 5% and 15%. For the  $tW_{1L}$  and  $tW_{2L}$  analysis channels, the uncertainties vary between 5% and 30% across the  $m_a-m_{H^\pm}$  and  $m_a-\tan\beta$  planes, with the largest values obtained for samples characterised by low values of the  $H^\pm$  mass and independently of  $\tan\beta$ . For the  $tj_{1L}$  analysis channel, uncertainties are found to be between 15% and 5% as a function of increasing  $m_{H^\pm}$  for all  $\tan\beta$  values considered.

## 7 Results

The event yields for all SRs in the three analysis channels are reported in Tables 6 and 7 and are summarised in Fig. 9, where the significance for each of the SRs is also presented. The SM background expectations resulting from background-only fits are shown along with their statistical plus systematic uncertainties. No significant deviations from the expected yields are observed in any of the signal regions considered. The largest background contribution in the  $tW_{1L}$  and  $tj_{1L}$  analysis channel SRs arises from  $t\bar{t}$  production, whilst the contribution from  $t\bar{t}V$  is largest in the  $tW_{2L}$  SRs, with subdominant contributions from the  $t\bar{t}$ , single-top (including  $tWZ$ ) and diboson processes. Other non-negligible background sources are  $W$ +jets and  $Z$ +jets production.

Figures 10, 11, 12 show comparisons between the observed data and the post-fit SM predictions for some relevant kinematic distributions in the three analysis channels after applying all SR selection requirements except the one on the quantity shown (except for Figs. 10c and 11b, where all events in the SR are shown). For the  $tW_{1L}$  analysis channel, the  $m_T^{\text{lep}}$  and  $am_{T2}$  distributions are shown for all values of  $E_T^{\text{miss}}$  across the five bins. Similarly, for the  $tj_{1L}$  analysis channel, the number of forward jets and  $E_T^{\text{miss}}$  are shown for all BDT values above 0.6. The expected distributions for representative scenarios with different  $m_a$ ,  $m_{H^\pm}$ , and  $\tan\beta$  (depending on the analysis channel and SR considered) are shown for illustrative purposes. Reasonable agreement is found between data and SM predictions in all distributions, although a mild excess of data events is found in the  $tW_{2L}$  distributions, accounting for a discrepancy lower than  $2\sigma$  considering statistical and systematic uncertainties.

**Table 6** Background-only fit results for the  $tW_{1L}$  and  $tW_{2L}$  signal regions. The backgrounds which contribute only a small amount (rare processes such as triboson,  $t\bar{t}$ ,  $t\bar{t} WW$  and Higgs boson production processes, and non-prompt or misidentified leptons background) are grouped and labelled as ‘Others’. The quoted uncertainties of the fitted SM background include both the statistical and systematic uncertainties

	$SR_{tW_{1L}}^{Bin0}$	$SR_{tW_{1L}}^{Bin1}$	$SR_{tW_{1L}}^{Bin2}$	$SR_{tW_{1L}}^{Bin3}$	$SR_{tW_{1L}}^{Bin4}$	$SR_{tW_{2L}}$
Observed events	182	191	60	24	12	12
Fitted SM bkg events	$169 \pm 14$	$171 \pm 13$	$55 \pm 6$	$20.1 \pm 2.8$	$15.6 \pm 2.8$	$5.9 \pm 1.2$
$t\bar{t}$	$101 \pm 12$	$84 \pm 12$	$20 \pm 5$	$5.1 \pm 1.7$	$2.3 \pm 1.5$	$1.2 \pm 0.9$
Single top	$16.3 \pm 5.2$	$17.3 \pm 5.2$	$5.4 \pm 3.2$	$2.0 \pm 1.8$	$1.7^{+2.0}_{-1.7}$	$0.26^{+0.27}_{-0.26}$
$W$ +jets	$28 \pm 4$	$37.0 \pm 4.3$	$14.2 \pm 2.4$	$6 \pm 1$	$5.9 \pm 1.1$	–
$Z$ +jets	$2.0 \pm 0.9$	$1.1 \pm 0.7$	$0.3 \pm 0.1$	$0.15 \pm 0.04$	$0.15 \pm 0.02$	–
Diboson	$7.2 \pm 1.7$	$9.6 \pm 2.0$	$4.6 \pm 1.0$	$2.2 \pm 0.5$	$2.7 \pm 0.6$	$0.5 \pm 0.2$
$t\bar{t} V$	$12.3 \pm 1.4$	$19.5 \pm 3.5$	$8.7 \pm 1.2$	$4.0 \pm 0.7$	$2.5 \pm 0.5$	$2.9 \pm 0.7$
$tWZ$	$1.7 \pm 0.2$	$2.4 \pm 0.5$	$1.17 \pm 0.15$	$0.42 \pm 0.09$	$0.39 \pm 0.09$	$0.8 \pm 0.1$
Others	$0.6 \pm 0.1$	$0.6 \pm 0.1$	$0.17 \pm 0.02$	$0.06 \pm 0.02$	$0.03 \pm 0.01$	$0.16 \pm 0.08$

**Table 7** Background-only fit results for the  $tj_{1L}$  signal regions. The backgrounds which contribute only a small amount ( $Z$ +jets, rare processes such as  $tWZ$ , triboson,  $t\bar{t}$ ,  $t\bar{t} WW$  and Higgs boson production processes) are grouped and labelled as ‘Others’. The quoted uncertainties of the fitted SM background include both the statistical and systematic uncertainties

	$SR_{tj_{1L}}^{Bin0}$	$SR_{tj_{1L}}^{Bin1}$	$SR_{tj_{1L}}^{Bin2}$	$SR_{tj_{1L}}^{Bin3}$
Observed events	360	178	69	29
Fitted SM bkg events	$335 \pm 74$	$187 \pm 40$	$67 \pm 18$	$37 \pm 7$
$t\bar{t}$	$280 \pm 75$	$151 \pm 42$	$54 \pm 16$	$30 \pm 8$
$W$ +jets	$14.4 \pm 5.1$	$12.4 \pm 8.7$	$2.7^{+7.5}_{-2.7}$	<0.1
Single top	$27 \pm 14$	$13.2 \pm 7.5$	$5.7 \pm 3.7$	$3.8 \pm 2.5$
$t\bar{t} V$	$5.0 \pm 1.6$	$3.1 \pm 1.0$	$1.4 \pm 0.6$	$1.3 \pm 0.5$
Diboson	$3.3 \pm 1.0$	$2.5 \pm 0.8$	$1.4 \pm 0.5$	$0.8 \pm 0.3$
Others	$4.9 \pm 2.4$	$4.8 \pm 2.0$	$2.0 \pm 0.7$	$1.0 \pm 0.4$

### 7.1 Statistical combination of the $tW_{1L}$ and $tW_{2L}$ analysis channels

A statistical combination of results from the  $tW_{1L}$  and  $tW_{2L}$  channels is performed to maximise the sensitivity to  $tW$ +DM models. The simultaneous fit is performed such that the individual background normalisation factors,  $\mu_{t\bar{t}}^{1L}$ ,  $\mu_{t\bar{t}}^{2L}$ ,  $\mu_{W+jets}$  and  $\mu_{t\bar{t}V}$ , are constrained in the same regions as the respective, individual analyses to avoid extrapolations into a different phase space. Experimental uncertainties in the background and signal are evaluated using the same methods as described in Sect. 5 and correlated across channels. Modelling uncertainties from the same source for a given process are correlated, e.g. all modelling uncertainties for  $t\bar{t}$  are correlated across the regions. Signal systematic uncertainties are also correlated for the exclusion fits described in the next section.

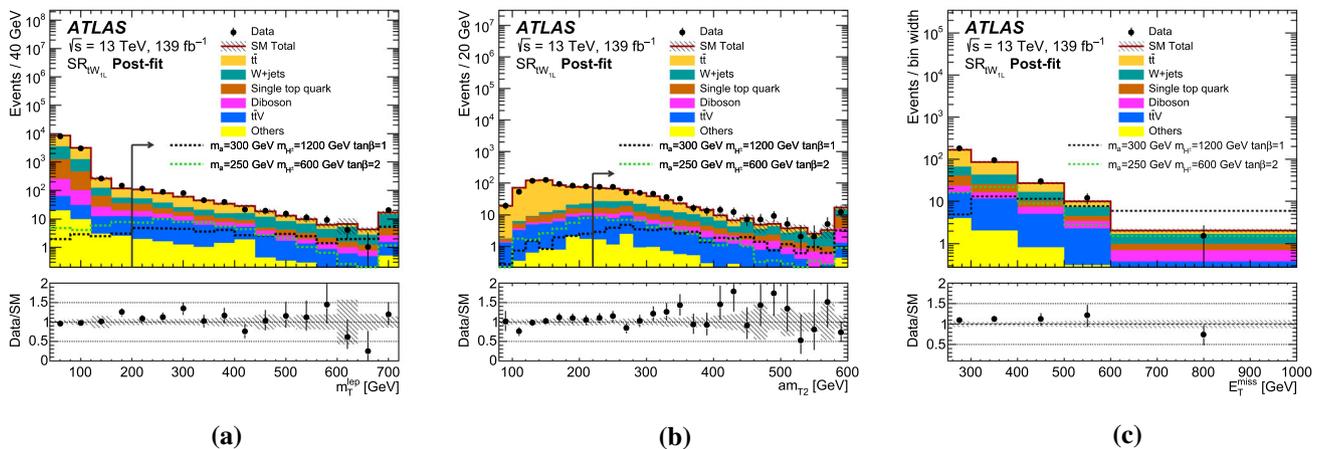
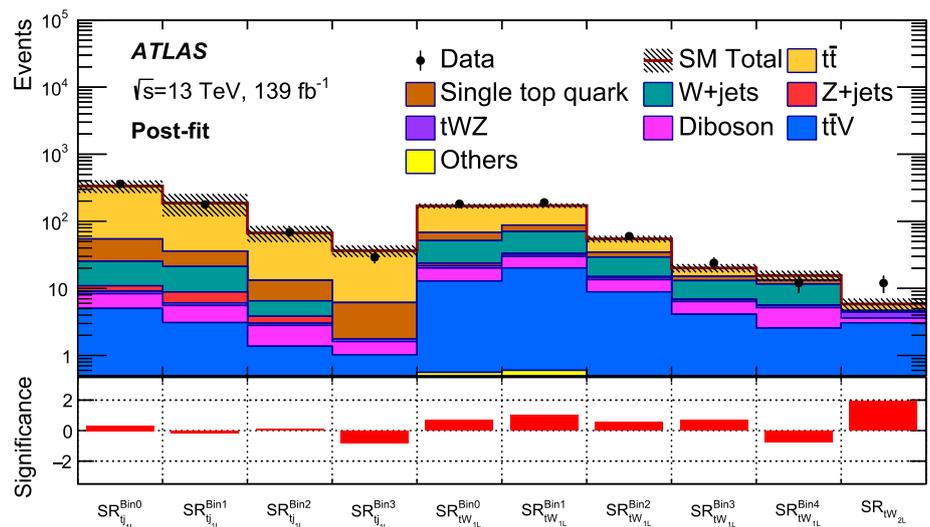
The predictions for SM backgrounds are, as expected, equivalent to those of the individual channels. In particular, the values for the  $\mu_{t\bar{t}}$  background normalisation factor are found to be consistent for  $tW_{1L}$  and  $tW_{2L}$  estimates,  $\mu_{t\bar{t}}^{1L} = 0.97 \pm 0.08$  and  $\mu_{t\bar{t}}^{2L} = 1.00 \pm 0.03$ , respectively.

### 7.2 Model-independent limits

The  $CL_s$  technique [93] is used to place 95% confidence level (CL) upper limits on event yields from physics BSM for each signal region (model-independent limits). The profile-likelihood-ratio test statistic is used to exclude the signal-plus-background hypotheses for specific signal models. When normalised to the integrated luminosity of the data sample, results can be interpreted as corresponding upper limits on the visible cross section,  $\sigma_{vis}$ , defined as the product of the BSM production cross section, the acceptance and the selection efficiency of a BSM signal. In the case of the  $tW_{1L}$  analysis channel, the  $E_T^{miss}$  bins are defined inclusively, i.e. all events above the lowest bin-threshold in  $E_T^{miss}$  are taken, to retain discovery potential. The SM predictions and their corresponding uncertainties are reported in Table 8. In the case of the  $tj_{1L}$  analysis channel, the last bin of the BDT score distribution, 0.9–1.0, is considered.

Table 9 summarises the observed ( $S_{obs}^{95}$ ) and expected ( $S_{exp}^{95}$ ) 95% CL upper limits on the number of BSM events and on  $\sigma_{vis}$  for all SRs. The  $p_0$ -values, which represent the probability of the SM background to fluctuate to the observed

**Fig. 9** Results of the background-only fit extrapolated to all SRs. The normalisation of the backgrounds is obtained from the fit to the CRs. The upper panel shows the observed number of events and the predicted background yields. The ‘Others’ category includes contributions from rare processes such as triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. All uncertainties defined in Sect. 6 are included in the uncertainty band. The lower panel shows the significance in each SR. The significance calculation is performed as described in Ref. [84]



**Fig. 10** Representative distributions of **a**  $m_T^{\text{lep}}$ , **b**  $a m_{T2}$  and **c**  $E_T^{\text{miss}}$  in the  $tW_{1L}$  channel. Observed data are compared with the SM background predictions extrapolated from the background-only fit. All SR selections except the one on the quantity shown are applied. The SR requirement is indicated by the arrow. The ‘Others’ category includes contributions from  $Z+jets$  and  $tWZ$  production, and rare processes such as triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. The expected

distributions for representative scenarios with different  $m_a$ ,  $m_{H^\pm}$ , and  $\tan\beta$  are shown for illustrative purposes. The overflow events, where present, are included in the last bin. The lower panels show the ratio of data to the background prediction. The hatched error bands indicate the combined experimental and MC statistical uncertainties on these background predictions

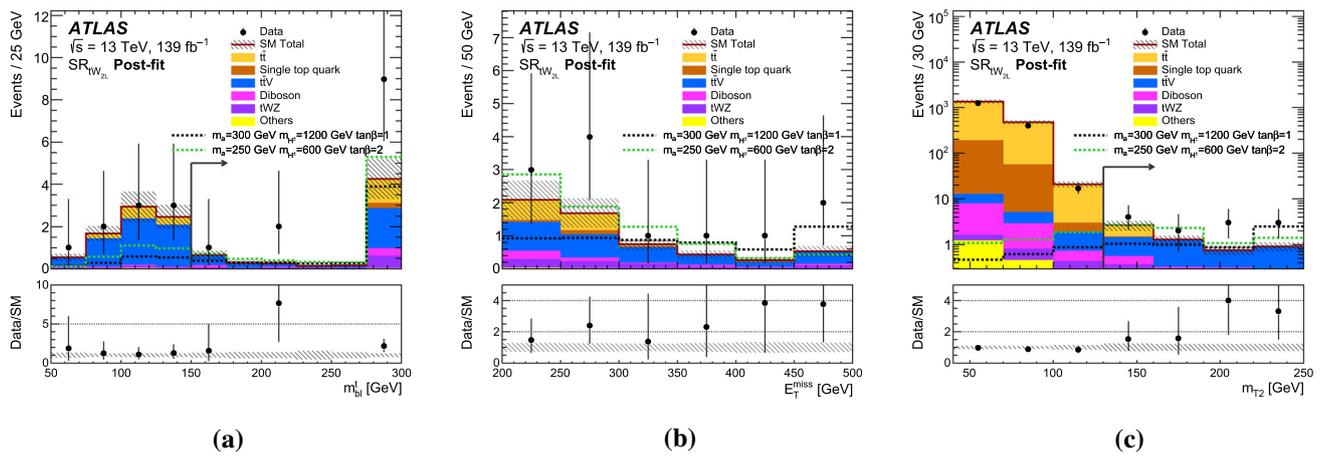
number of events or higher, are also provided and are capped at  $p_0 = 0.5$ ; the associated significance is provided in parentheses.

### 7.3 Model-dependent limits

Model-dependent exclusion limits are placed on the common signal parameters  $m_a$ ,  $m_{H^\pm}$ , and  $\tan\beta$  in the 2HDM+ $a$  models considered in the analysis. Following the prescriptions in Ref. [5], the masses of the bosons  $H$ ,  $H^\pm$  and  $A$  are set to be equal. The three quartic couplings between the scalar doublets and the  $a$  boson ( $\lambda_{P1}$ ,  $\lambda_{P2}$  and  $\lambda_3$ ) are all set equal to 3, in order to reduce the number of parameters and evade the constraints from electroweak precision mea-

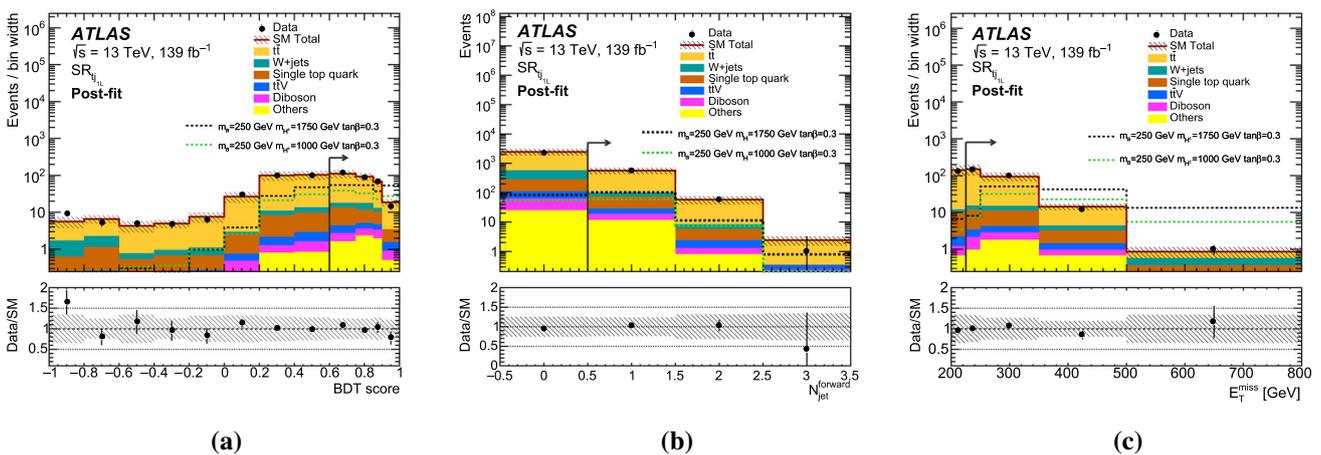
surements [18]. To further reduce the parameter space, unitary couplings between the  $a$  boson mediator and the DM particle  $\chi$  ( $g_\chi = 1$ ) are considered, with the DM particle mass set to  $m_\chi = 10$  GeV. The mixing angle  $\theta$  is fixed at  $\sin\theta = 1/\sqrt{2}$ , yielding full mixing between the  $a$  and  $A$  bosons and the largest cross sections for the processes of interest. Two sets of samples are considered,<sup>2</sup> varying either the  $(m_a, m_{H^\pm})$  parameters and setting  $\tan\beta$  to unity, or vary-

<sup>2</sup> As pointed out in Ref. [5], for the two considered sets of samples, only values  $m_{H^\pm} < 600$  GeV provide a bounded-from-below scalar potential [20] for the 2HDM+ $a$  model. This constraint can be relaxed up to a factor 2 if the quartic coupling  $\lambda_3$  assumes a value closer to the perturbativity limit and they can be relaxed further in more general 2HDMs containing additional quartic couplings [94], as discussed in Ref. [95].



**Fig. 11** Representative distributions of **a**  $m_{b\ell}^t$ , **b**  $E_T^{\text{miss}}$  and **c**  $m_{T2}$  in the  $tW_{2L}$  channel. Observed data are compared with the SM background predictions extrapolated from the background-only fit. All SR selections except the one on the quantity shown are applied. The SR requirement is indicated by the arrow. As the  $m_{b\ell}^t$  is defined for events with at least two jets, the events with exactly one jet are included in the overflow bin. The ‘Others’ category includes contributions from rare processes

such as triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. The expected distributions for representative scenarios with different  $m_a$ ,  $m_{H^\pm}$ , and  $\tan\beta$  are shown for illustrative purposes. The overflow events, where present, are included in the last bin. The lower panels show the ratio of data to the background prediction. The hatched error bands indicate the combined experimental and MC statistical uncertainties on these background predictions



**Fig. 12** Representative distributions of **a** BDT score, **b**  $N_{\text{jet}}^{\text{forward}}$  and **c**  $E_T^{\text{miss}}$  in the  $tJ_{1L}$  channel. Observed data are compared with the SM background predictions extrapolated from the background-only fit. All SR selections except the one on the quantity shown are applied. The SR requirement is indicated by the arrow. The ‘Others’ category includes contributions from  $Z$ +jets and  $tWZ$  production, and rare processes such

as triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}WW$ , and Higgs boson production processes. The expected distributions for representative scenarios with different  $m_a$ ,  $m_{H^\pm}$ , and  $\tan\beta$  are shown for illustrative purposes. The overflow events, where present, are included in the last bin. The lower panels show the ratio of data to the background prediction. The hatched error bands indicate the combined experimental and MC statistical uncertainties on these background predictions

ing the  $(m_{H^\pm}, \tan\beta)$  parameters and setting  $m_a = 250$  GeV. The fit procedure takes into account correlations in the yield predictions between control and signal regions due to common background normalisation parameters and systematic uncertainties. The experimental systematic uncertainties in the signal are taken into account for the calculation and are assumed to be fully correlated with those in the SM background. The results of the combined fit for the  $tW_{1L}$  and  $tW_{2L}$

channels are interpreted using the sum of the respective signal yield estimates for each generated sample, with overlap between the samples removed according to the procedure illustrated in Ref. [22].

Figure 13a, b show the observed and expected exclusion contours as functions of  $(m_a, m_{H^\pm})$  and  $(m_{H^\pm}, \tan\beta)$ , respectively, for the  $tW_{1L}$  and  $tW_{2L}$  channels, presented both individually and statistically combined. In this case, only the

**Table 8** Background-only fit results for  $tW_{\text{IL}}$  signal region bins for model-independent limits. Events with  $E_T^{\text{miss}}$  above the lowest bin-threshold are retained in each bin. This is indicated by value  $X$  in  $\text{SR}_{tW_{\text{IL}}}^X$ . The backgrounds which contribute only a small amount (rare

processes such as  $tWZ$ , triboson,  $t\bar{t}t\bar{t}$ ,  $t\bar{t}WW$  and Higgs boson production processes) are grouped and labelled as ‘Others’. The quoted uncertainties of the fitted SM background include both the statistical and systematic uncertainties

	$\text{SR}_{tW_{\text{IL}}}^{250}$	$\text{SR}_{tW_{\text{IL}}}^{300}$	$\text{SR}_{tW_{\text{IL}}}^{400}$	$\text{SR}_{tW_{\text{IL}}}^{500}$	$\text{SR}_{tW_{\text{IL}}}^{600}$
Observed events	469	287	96	36	12
Fitted SM bkg events	$431 \pm 27$	$262 \pm 20$	$91 \pm 10$	$36 \pm 5$	$15.5 \pm 2.8$
$t\bar{t}$	$213 \pm 25$	$111 \pm 18$	$28 \pm 7$	$7.5 \pm 2.9$	$2.3 \pm 1.5$
Single top	$43 \pm 15$	$27 \pm 12$	$9 \pm 7$	$3.9 \pm 3.8$	$1.7_{-1.7}^{+2.0}$
$W$ +jets	$91 \pm 8$	$63 \pm 5$	$26 \pm 3$	$12.0 \pm 1.7$	$5.9 \pm 1.1$
$Z$ +jets	$3.8 \pm 1.0$	$1.7 \pm 0.7$	$0.6 \pm 0.1$	$0.30 \pm 0.05$	$0.15 \pm 0.02$
Diboson	$26 \pm 5$	$19.0 \pm 3.9$	$9 \pm 2$	$4.8 \pm 1.0$	$2.6 \pm 0.6$
$t\bar{t}V$	$47 \pm 3$	$34.7 \pm 2.4$	$15.3 \pm 1.2$	$6.6 \pm 0.5$	$2.5 \pm 0.3$
Others	$7.5 \pm 0.5$	$5.3 \pm 0.4$	$2.3 \pm 0.1$	$0.9 \pm 0.1$	$0.40 \pm 0.05$

**Table 9** The 95% CL upper limits on the visible cross section ( $\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ ) and on the number of signal events ( $S_{\text{obs}}^{95}$ ) for all SRs and analysis channels as detailed in the text. The fourth column ( $S_{\text{exp}}^{95}$ ) shows the 95% CL upper limit on the number of signal events, given the expected

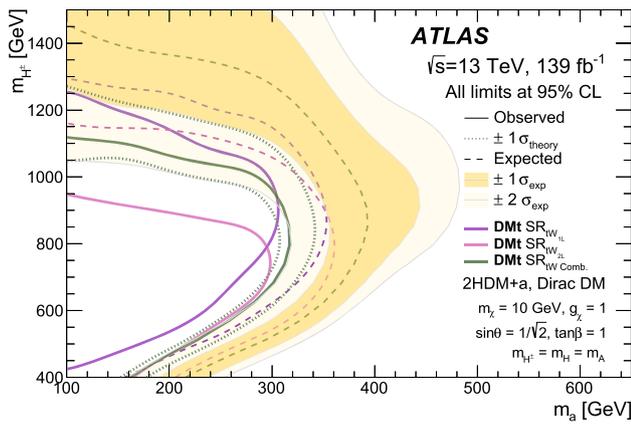
number (and  $\pm 1\sigma$  exclusions of the expectation) of background events. The last two columns indicate the  $CL_B$  value, i.e. the confidence level observed for the background-only hypothesis, and the discovery  $p$ -value ( $p(s = 0)$ ). The associated significance is provided in parentheses

Signal channel	$\langle\epsilon\sigma\rangle_{\text{obs}}^{95}$ [fb]	$S_{\text{obs}}^{95}$	$S_{\text{exp}}^{95}$	$CL_B$	$p(s = 0)$ (Z)
$\text{SR}_{tW_{\text{IL}}}^{250}$	0.72	100.6	$67_{-16}^{+33}$	0.85	0.12 (1.16)
$\text{SR}_{tW_{\text{IL}}}^{300}$	0.51	70.8	$54 \pm 16$	0.85	0.15 (1.02)
$\text{SR}_{tW_{\text{IL}}}^{400}$	0.24	32.9	$29_{-6}^{+10}$	0.64	0.30 (0.52)
$\text{SR}_{tW_{\text{IL}}}^{500}$	0.14	18.9	$19_{-5}^{+8}$	0.52	0.45 (0.13)
$\text{SR}_{tW_{\text{IL}}}^{600}$	0.08	10.6	$12_{-4}^{+3}$	0.24	0.94 (−1.54)
$\text{SR}_{tW_{2L}}$	0.10	13.8	$7.3_{-1.1}^{+2.9}$	0.97	0.02 (2.07)
$\text{SR}_{tj_{\text{IL}}}(\text{BDT} > 0.9)$	0.10	14.4	$19_{-5}^{+6}$	0.24	0.50 (0.00)

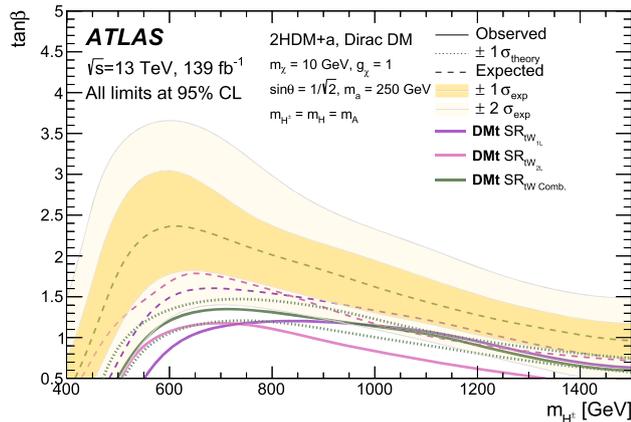
$DMt$  contribution of the signal is taken into account to better illustrate the sensitivity to single-top signatures. Figure 14a, b show the observed and expected exclusion contours for the same models, but also include the expected contributions from the  $DMt\bar{t}$  process. Figures 13 and 14 also report the  $1\sigma$  and  $2\sigma$  uncertainty bands around the observed limit contour, as well as the variations obtained by changing the theoretical cross-section predictions for signal to be 15% above or below the nominal value (as this is expected to be largest uncertainty in the signal yields across the plane). For low  $H^\pm$  masses,  $DMt$  production generally dominates  $DMt\bar{t}$  production, due to the contribution from the resonant  $H^\pm$  diagrams, except when the mass difference  $m_{H^\pm} - m_a$  is small enough to suppress the branching fraction of  $H^\pm \rightarrow Wa$  decay relative to  $H^\pm \rightarrow t\bar{b}$ . On the other hand,  $DMt\bar{t}$  contributions are dominant at high  $m_{H^\pm}$ . The width of  $H^\pm$  also increases at high  $m_{H^\pm}$ , and it is about 20% of its mass for  $m_{H^\pm} = 1$  TeV. Moreover, as studied in Ref. [22], the  $DMt\bar{t}$  cross section is proportional to  $1/\tan^2\beta$ , whereas the  $H^\pm$  production cross section has a more complex dependence, with a minimum for

$\tan\beta \sim 10$  and an enhancement for high values of  $\tan\beta$ . For  $\tan\beta = 1$  and  $m_{H^\pm} \sim m_a + m_W$ , the  $DMt\bar{t}$  cross section also dominates the  $DMt$  cross section. Assuming  $m_\chi = 10$  GeV and  $g_\chi = 1$ , masses of  $a$  below 190 GeV are excluded at 95% CL for all values of  $m_{H^\pm}$  in the range 400–1400 GeV, and up to 330 GeV for  $m_{H^\pm}$  around 800 GeV. When only  $DMt$  contributions are taken into account, the constraints on  $m_a$  decrease by 20–50 GeV. In the case where  $m_a = 250$  GeV, all values of  $m_{H^\pm}$  between 450 GeV and 1.5 TeV are excluded for  $\tan\beta$  around and below unity, and scenarios with  $\tan\beta$  below 1.5 are excluded for masses of  $H^\pm$  around 800 GeV.

The sensitivity of the  $tj_{\text{IL}}$  channel is small compared to the other analysis channels. It targets the  $t$ -channel production component of the  $DMt$  signal, which has a smaller cross section with respect to the  $tW$ +DM process. The observed and expected cross-section limits at 95% CL as a function of  $m_{H^\pm}$  for two representative values of  $\tan\beta$  are shown in Fig. 15 assuming a fixed value of  $m_a = 250$  GeV. The limits are shown as a multiple of  $\sigma_{\text{BSM}}$ , the theoretical cross section of the  $t$ -channel DM production process. For  $\tan\beta =$



(a) DMt,  $m_a$ - $m_{H^\pm}$  plane



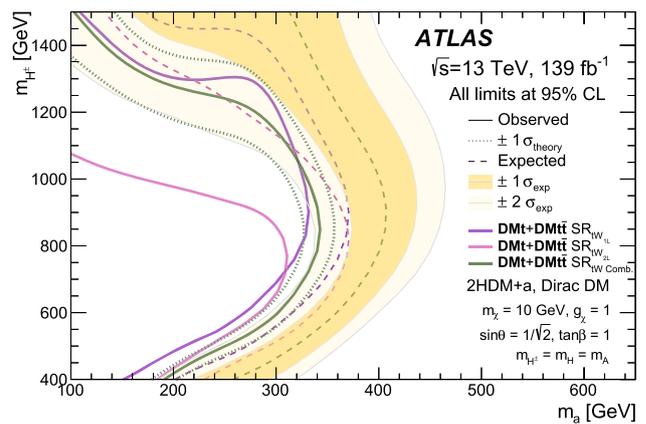
(b) DMt,  $m_{H^\pm}$ - $\tan\beta$  plane

**Fig. 13** The expected and observed exclusion contours as a function of  $(m_a, m_{H^\pm})$  (top) and  $(m_{H^\pm}, \tan\beta)$  (bottom), assuming only  $tW$ +DM contributions, for the individual  $tW_{1L}$  (purple line) and  $tW_{2L}$  (pink line) analysis channels, and for their statistical combination (green line). Experimental and theoretical systematic uncertainties, as described in Sect. 6, are applied to background and signal samples and illustrated by the  $\pm 1$  standard-deviation and  $\pm 2$  standard-deviation yellow bands and the green dotted contour lines, respectively, for the statistical combination

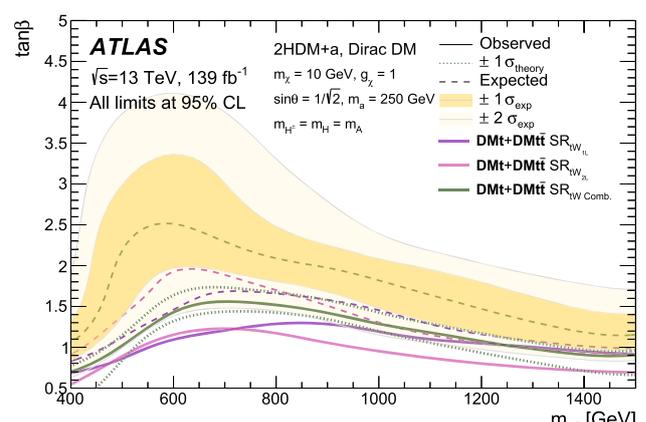
0.3,  $H^\pm$  masses above 900 GeV are excluded under these hypotheses, whilst no exclusion is obtained for  $\tan\beta = 0.5$ .

### 8 Conclusion

A search for dark matter has been performed in the context of a two-Higgs-doublet model together with an additional pseudoscalar mediator,  $a$ , which decays into the dark-matter particles. Processes where the pseudoscalar mediator is produced in association with a single top quark in the 2HDM+ $a$  model are explored for the first time at the LHC. Several final states which include either one or two leptons (electrons or muons) and a significant amount of missing trans-



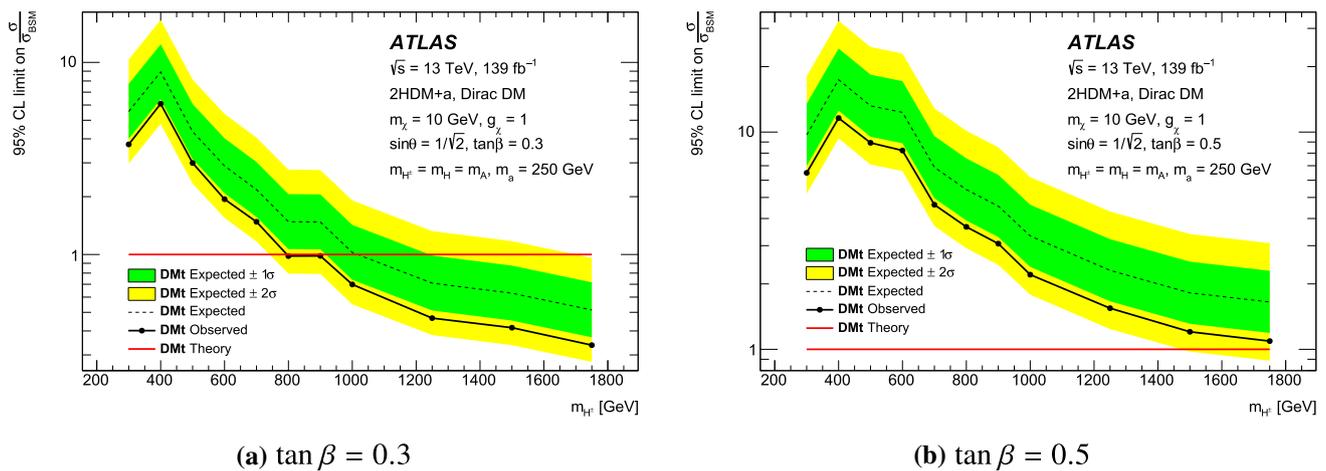
(a) DMt+DMt $\bar{t}$ ,  $m_a$ - $m_{H^\pm}$  plane



(b) DMt+DMt $\bar{t}$ ,  $m_{H^\pm}$ - $\tan\beta$  plane

**Fig. 14** The expected and observed exclusion contours as a function of  $(m_a, m_{H^\pm})$  (top) and  $(m_{H^\pm}, \tan\beta)$  (bottom), assuming DMt+DMt $\bar{t}$  and DMt contributions, for the individual  $tW_{1L}$  (purple line) and  $tW_{2L}$  (pink line) analysis channels, and for their statistical combination (green line). Experimental and theoretical systematic uncertainties, as described in Sect. 6, are applied to background and signal samples and illustrated by the  $\pm 1$  standard-deviation and  $\pm 2$  standard-deviation yellow bands and the green dotted contour lines, respectively, for the statistical combination

verse momentum are considered. The analysis makes use of proton–proton collision data at  $\sqrt{s} = 13$  TeV collected by the ATLAS experiment during LHC Run 2 (2015–2018), corresponding to an integrated luminosity of  $139 \text{ fb}^{-1}$ . No significant excess above the Standard Model predictions is found. The results are expressed as 95% confidence-level limits on the 2HDM+ $a$  signal models considered. Assuming dark-matter particles with mass  $m_\chi = 10$  GeV and coupling  $g_\chi = 1$  to the mediator, and full mixing between the  $a$  and  $A$  bosons, masses of  $a$  below 200 GeV are excluded at 95% CL for all values of  $m_{H^\pm}$  in the range 400–1400 GeV, and up to 330 GeV for  $m_{H^\pm}$  around 900 GeV. For  $m_a = 250$  GeV, all values of  $m_{H^\pm}$  below 1.5 TeV are excluded for  $\tan\beta$  below



**Fig. 15** The expected and observed cross-section exclusion limits as a function of  $m_{H^\pm}$  in the  $t_{j1L}$  analysis channel for signal models with  $m_a = 250$  GeV, and **a**  $\tan\beta = 0.3$  and **b**  $\tan\beta = 0.5$ . The theoretical cross section of the  $t$ -channel DM production process is denoted by ‘Theory’

unity, and scenarios with  $\tan\beta$  below 1.5 are excluded for masses of  $H^\pm$  around 800 GeV.

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**Data Availability Statement** This manuscript has no associated data or the data will not be deposited. [Authors’ comment: All ATLAS scientific output is published in journals, and preliminary results are made available in Conference Notes. All are openly available, without restriction on use by external parties beyond copyright law and the standard conditions agreed by CERN. Data associated with journal publications are also made available: tables and data from plots (e.g. cross section values, likelihood profiles, selection efficiencies, cross section limits,...) are stored in appropriate repositories such as HEPDATA (<http://hepdata.cedar.ac.uk/>). ATLAS also strives to make additional material related to the paper available that allows a reinterpretation of the data in the context of new theoretical models. For example, an extended encapsulation of the analysis is often provided for measurements in the framework of RIVET (<http://rivet.hepforge.org/>). The above sentence is taken from the ATLAS Data Access Policy. Please make reference to it saying that it is a public document that can be downloaded from here: <http://opendata.cern.ch/record/413> [opendata.cern.ch.]

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