Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV $pp$ collisions of ATLAS data

The ATLAS Collaboration

Abstract

A search for the stop, the supersymmetric partner of the top quark, is conducted in final states with one isolated electron or muon, jets, and missing transverse momentum using the 2015 LHC $pp$ collision data at a centre-of-mass energy of $\sqrt{s} = 13$ GeV recorded by the ATLAS detector and corresponding to an integrated luminosity of 3.2 fb$^{-1}$. The analysis targets two types of signal models: gluino-mediated pair production of stops with a nearly mass degenerate stop and neutralino; and direct pair production of stops, decaying to the top quark and the lightest neutralino. The experimental signature in both signal scenarios is similar to that of a top quark pair produced in association with large missing transverse momentum, $t\bar{t} + E_T^{\text{miss}}$. No significant excess over the Standard Model prediction is observed, and exclusion limits on gluino and stop masses are set at 95 % CL. The results extend the LHC Run 1 exclusion limit on the gluino mass up to 1460 GeV in the gluino-mediated scenario in the high gluino and low stop mass region, and for the direct stop model add an excluded stop mass region from 745 to 780 GeV for a massless lightest neutralino.
1 Introduction

Supersymmetry (SUSY) [1–6] is a natural solution [7, 8] to the hierarchy problem [9–12]. The superpartner of the top quark \( \tilde{t} \) (top squark or stop) is expected to be relatively light due to its large contribution to the Higgs boson mass radiative corrections [13, 14]. For reasons such as gauge unification [15] and the 2-loop radiative corrections to the Higgs boson mass [16, 17], one may also expect a TeV scale for the mass of the gluino, the superpartner of the gluon. A common theoretical strategy for avoiding strong constraints from the non-observation of proton decay [18] is to introduce a multiplicative quantum number called \( R \)-parity. If \( R \)-parity is conserved [19] SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable. This note follows the typical assumption that the lightest neutralino \( \chi_1^0 \) is the LSP. Since the \( \chi_1^0 \) interacts only weakly it can serve as a candidate for dark matter [20, 21].

This note presents a search targeting the lighter stop \( \tilde{t}_1 \) in two signal scenarios: gluino-mediated pair production of the \( \tilde{t}_1 \) with a small \( \tilde{t}_1 \)-LSP mass splitting, and direct pair production of the \( \tilde{t}_1 \), both illustrated by the diagrams in Fig. 1. The former scenario refers to pair production of gluinos, each decaying to the top quark and the \( \tilde{t}_1 \). In this scenario, the mass difference between the gluino and the \( \tilde{t}_1 \) is assumed to be well above the top quark mass, while the mass difference between the \( \tilde{t}_1 \) and the LSP is assumed to be significantly smaller than the \( W \) boson mass. As a result, the visible \( \tilde{t}_1 \) decay products have low momentum, typically below the reconstruction and identification thresholds. This scenario is motivated by the dark matter relic density, which is generally too large in the Minimal Supersymmetric Standard Model [22, 23] but can be regulated by co-annihilation of the stop and the neutralino [24–26]. In the second scenario, the two directly produced \( \tilde{t}_1 \) are each assumed to decay to the top quark and the LSP. This model is interesting as it is independent of the gluino mass, which is more weakly constrained by naturalness arguments than the stop mass.

Experimentally, the final states of the two scenarios are similar, and the detector signature consists of the decay products of a pair of top quarks\(^3\) and large missing transverse momentum (\( \not{p}_T^{\text{miss}} \), where the magnitude is referred to as \( E_T^{\text{miss}} \)) from the two LSPs: \( t\bar{t} + \not{E}_T^{\text{miss}} \). The main difference between the two scenarios is that the production cross-section for gluino pairs is about a factor 50 higher than for \( \tilde{t}_1 \) pairs of the same mass. The results are also re-interpreted in a model of pair produced vector-like top quarks \( T \) (referred to as VLQ) [27–29], for which the decay mode \( T \to tZ \) with \( Z \to \nu\bar{\nu} \) has a phenomenology similar to that of direct stop pair production with \( \tilde{t}_1 \to t\chi_1^0 \).

The analysis presented here – which is based on previous ATLAS searches for the same signature [30, 31] – targets the one-lepton final state where the \( W \) boson from one of the top quarks decays to an electron or muon (either directly or via a \( \tau \)) and the \( W \) boson from the other top quark decays hadronically. The dominant background processes are: the production of \( t\bar{t} \) and the associated production of a top quark and a \( W \) boson (single top \( W_t \)); \( t\bar{t} + Z(\to \nu\bar{\nu}) \); and the associated production of \( W \) bosons and jets (\( W+jets \)). The search uses the ATLAS data collected in proton-proton (\( pp \)) collisions in 2015 corresponding to an integrated luminosity of 3.2 fb\(^{-1}\) at a centre-of-mass energy of \( \sqrt{s} = 13 \) TeV. The ATLAS Run 1 searches for gluino-mediated stop production and direct stop pair production are summarized in Ref. [32] and [33],

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\(^1\) The charginos \( \tilde{\chi}_{1,2}^\pm \) and neutralinos \( \tilde{\chi}_{1,2,3,4}^0 \) are the mass eigenstates formed from the linear superposition of the charged and neutral SUSY partners of the Higgs and electroweak gauge bosons (higgsinos, winos and binos).

\(^2\) The superpartners of the left- and right-handed top quarks, \( \tilde{t}_L \) and \( \tilde{t}_R \), mix to form the two mass eigenstates \( \tilde{t}_1 \) and \( \tilde{t}_2 \), where \( \tilde{t}_1 \) is the lighter one.

\(^3\) Due to the Majorana nature of the gluino, in the gluino-mediated model, each of the two ‘visible’ top quarks can independently be a top or an anti-top quark. Hereafter, the term \( \tilde{t}\bar{t} \) can be taken to refer to any combination of \( t \) and \( \bar{t} \).
respectively. The CMS collaboration has performed similar searches in Run 1 for gluino-mediated stop production [34] and direct stop pair production [35–39].

This document is organized as follows. The ATLAS detector, dataset and trigger are described in Section 2 and the corresponding set of simulations are detailed in Section 3. Section 4 presents an overview of the assignment of detector-level measurements to physical objects and the construction of discriminating variables. These variables are used in Section 5 to construct the signal event selections. The background estimation procedure (Section 6) and systematic uncertainties (Section 7) are described before the results are presented in Section 8. Section 9 contains concluding remarks.

2 ATLAS detector and dataset

The ATLAS detector [40] is a multi purpose particle physics detector with nearly 4π coverage in solid angle around the collision point. It consists of an inner tracking detector (ID), surrounded by a superconducting solenoid providing a 2 T axial magnetic field, a system of calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroid magnets. The ID provides charged-particle tracking in the range \(|\eta| < 2.5\) using three technologies: silicon pixel and silicon microstrip tracking detectors, and a transition radiation tracker. During the LHC shutdown between Run 1 and Run 2, a new innermost layer of silicon pixels has been added, which improves the track impact parameter resolution and vertex position resolution performance [41]. High-granularity electromagnetic and hadronic calorimeters cover the region \(|\eta| < 4.9\). The central hadronic calorimeter is a sampling calorimeter with scintillator tiles as the active medium and steel absorbers. All the electromagnetic calorimeters, as well as the endcap and forward hadronic calorimeters, are sampling calorimeters with liquid argon as the active medium and lead, copper, or tungsten absorber. The MS consists of three layers of high-precision tracking chambers.
with coverage up to $|\eta| = 2.7$ and dedicated chambers for triggering in the region $|\eta| < 2.4$. Events are selected by a two-level trigger system, the first level is a hardware-based system, while the second is a software-based system.

The 2015 LHC collision data used in this analysis has a mean number of additional $pp$ interactions per bunch crossing (pileup) of approximately 14, and a bunch spacing of 25 ns. Following requirements based on beam and detector conditions and data quality, the dataset corresponds to an integrated luminosity of $3.2 \, \text{fb}^{-1}$ with an associated uncertainty of 5%. The uncertainty is derived following the same methodology as that detailed in Ref. [42]. Events used for this search were recorded using a trigger logic that accepts events with $E_{\text{T}}^{\text{miss}} > 200 \, \text{GeV}$ requirement and is $> 99\%$ efficient for events passing an offline computed $E_{\text{T}}^{\text{miss}} > 200 \, \text{GeV}$ requirement and is $> 99\%$ efficient for events passing all signal selections. An additional data sample used to estimate one of the background processes was recorded with a trigger requiring a photon with transverse momentum $p_T > 120 \, \text{GeV}$.

3 Monte Carlo Simulations

Samples of Monte Carlo (MC) simulated events are used for the description of the background and to model the SUSY signals. Several matrix element (ME) generators are combined with parton shower (PS) generators. Signal SUSY samples are generated at leading order (LO) with MG5_aMC 2 [43] while VLQ signal samples are generated at LO with Proton v2.2 [44, 45]. All signal samples are interfaced with Pythia 8.186 [46]. Background samples use one of three setups:

- MG5_aMC 2 interfaced with Pythia 8 [46] or Herwig++ using the CKKW-L [47] or the MC@NLO method for matching a LO or next-to-leading-order (NLO) ME to the PS, respectively.
- Powheg-Box [48–52] interfaced to Pythia 6 [53] or Herwig++ using the Powheg method [54, 55] for matching the NLO ME to the PS.
- Sherpa 2.1.1 [56] using Comix [57] and OpenLoops [58] ME generators interfaced with the Sherpa parton shower [59].

The CT10 [60] parton distribution function (PDF) is used for ME calculations with Sherpa and Powheg-Box and the NNPDF2.3 [61] PDF is used for samples generated with MG5_aMC, except for the NLO samples which use either CT10 or NNPDF3.0 [62]. The CTEQ6L1 [63] LO PDF along with the P2012 [64] set of underlying event tuned parameters (UE tune) is used for Pythia 6, the NNPDF2.3 LO PDF and the A14 UE tune [65] is used for Pythia 8, and the CT10 PDF with the default author UE tune is used for the Sherpa samples. The samples produced with MG5_aMC, Powheg-Box and Protons all use EvtGen v1.2.0 [66] for the modelling of $b$-hadron decays. The simulation setup is summarized in Table 1 and more details can be found in Ref. [67–70] for $t\bar{t}$ and single top, W/Z+jets, dibosons, and $t\bar{t} + W/Z$, respectively. Additional samples aside from those shown in Table 1 are used to assess theoretical modeling uncertainties and will be discussed in Section 7.

In the gluino-mediated production the stop is assumed to decay via $\tilde{t}_1 \to c + \chi^0_1$ with a 100% branching ratio and with a default mass splitting $m_{\tilde{t}_1} - m_{\chi^0_1} = 5 \, \text{GeV}$. Alternative samples with larger mass splitting and/or replacing the two-body stop decay by a four-body stop decay $\tilde{t}_1 \to b f f' \chi^0_1$, where $f f'$ is a fermion-antifermion pair, are produced for additional studies. The gluinos and stops are assumed to decay promptly. In the direct stop pair production samples, the $\tilde{t}_1$ is chosen to be mostly the partner of
the right-handed top quark and the \( \tilde{\chi}^0 \) to be a pure bino. This choice is consistent with a large branching ratio for the given \( t\bar{t} \) decay. Different hypotheses for the left/right mixing in the stop sector and the nature of the neutralino lead to different acceptance values. The acceptance is affected because the polarization of the top quark changes as a function of the field content of the supersymmetric particles, which impacts the boost of the lepton in the top quark decay. Signal grids are generated for both the gluino and stop pair production models. The grid spacing on the gluino/stop and stop/neutralino masses varies between 25 and 100 GeV.

All the MC samples are normalized to the highest order (in \( \alpha_s \)) cross-section available, as indicated in the last column of Table 1. The cross-sections for the pair and single production of top quarks as well as for the signal processes also include resummation of soft gluon emission to next-to-next-to-leading logarithmic NNLL and next-to-leading logarithmic NLL accuracy, respectively. As will be described in Section 6.1.3, it is important that the simulated \( t\bar{t} + \gamma \) and \( t\bar{t} + Z \) events are as similar as possible. Therefore, a small 4% correction is applied to the \( t\bar{t} + \gamma \) cross-section to account for a different PDF, factorization/renormalization scale, and the number of partons from the matrix element.\(^5\) The same NLO QCD \( k \)-factor is then applied to the \( t\bar{t} + \gamma \) process as is used for the \( t\bar{t} + Z (\to \nu\bar{\nu}) \) process \(^4\). This choice is motivated by the similarity of QCD calculations for the two processes as well as empirical studies of the ratio of \( k \)-factors computed as a function of the boson \( p_T \). Further information about the \( k \)-factor and its uncertainty is given in Section 7. The cross-sections for the \( t\bar{t}, W+\text{jets}, \) and \( Wt \) processes are used for cross checks and optimization studies while for the final results these processes are normalized to data in control regions.

All background samples, except for the \( t\bar{t} + \gamma \) sample, are processed with the full simulation of the ATLAS detector \(^8\) based on Geant 4 \(^8\). The signal samples and the \( t\bar{t} + \gamma \) sample are processed with a fast simulation \(^8\) of the ATLAS detector with parameterized showers in the calorimeters. All samples are produced with varying numbers of simulated minimum-bias interactions generated with Pythia 8 overlaid on the hard-scattering event to account for pileup from multiple \( pp \) interactions in the same or nearby bunch crossings. The average number of interactions per bunch crossing is reweighted to match the

\(^5\) The \( \tilde{R} \) component is given by the the off-diagonal entry of the stop mixing matrix. The \( t\bar{t} \) decays in the direct stop pair production samples are performed by Pythia and produce unpolarized top quarks. The events are reweighted to obtain a stop mixing equivalent to a matrix with (off-)diagonal entries of approximately (±0.83) 0.55. The event weights depend on the angular distributions of the top decay products \(^8\).

\(^6\) The \( t\bar{t} + \gamma \) sample uses a fixed factorization/renormalization scale of \( 2 \times m_{top} \) with no extra partons in the ME, whereas \( t\bar{t} + Z \) is generated with up to two partons. The top decay is performed in MG5_aMC for \( t\bar{t} + \gamma \) to account for hard photon radiation from the top decay products that is a \( \sim 15\% \) effect for \( p_T^\gamma \sim 120 \text{ GeV} \).
distribution in data. Furthermore, the simulated samples are reweighted to account for small differences in the performance of the reconstruction and identification of physics objects with respect to those measured in data [87].

4 Event Reconstruction and Selection

All events must pass a series of quality criteria before being considered for further use. The reconstructed primary vertex with the highest $\sum p_T^2$ must have at least two associated tracks. In this analysis, physics objects are labeled as either baseline or signal depending on various quality and kinematic requirements, where the latter describes a tighter selection of the former. Baseline objects are used to distinguish between the physics objects in the event and to compute the missing transverse momentum. Baseline leptons are also used to apply a second-lepton veto to suppress dilepton $t\bar{t}$ and $Wt$ events.

Electron candidates are reconstructed from electromagnetic calorimeter cell clusters that are matched to ID tracks. Baseline electrons are required to have $p_T > 7 \text{ GeV}$, $|\eta| < 2.47$, and pass ‘VeryLoose’ likelihood identification criteria which are defined following the same methodology described in Ref. [88]. Signal electrons must pass all baseline requirements and in addition have $p_T > 25 \text{ GeV}$, satisfy the ‘Loose’ likelihood identification criteria of Ref. [88], and have impact parameters along the beam direction ($z_0$) and in the transverse plane ($d_0$) that satisfy $|z_0 \sin \theta| < 0.5 \text{ mm}$ and $|d_0/\sigma_{d_0}| < 5$, where $\sigma_{d_0}$ is the uncertainty of $d_0$. Furthermore, signal electrons must be isolated, where the criteria use track-based information to obtain a flat 99% efficiency as derived from $Z$ to two leptons MC samples and confirmed in data.

Muons are reconstructed from combined tracks that are formed from the ID and MS, ID tracks matched to muon segments, stand-alone MS tracks, and ID tracks matched to an energy deposit in the calorimeter compatible with a minimum ionizing particle (referred to as calo-tagged muon) [89]. Baseline muons are required to have $p_T > 6 \text{ GeV}$, $|\eta| < 2.7$, and pass the ‘Loose’ identification criteria described in Ref. [89]. Signal muons must pass all baseline requirements and in addition have $p_T > 25 \text{ GeV}$, and have impact parameters $|z_0 \sin \theta| < 0.5 \text{ mm}$ and $|d_0/\sigma_{d_0}| < 3$. Furthermore, signal muons must be isolated according to isolation criteria similar to those used for signal electrons, yielding the same efficiency.

Photons are not used in the main event selection and give rise to extra jet or electron candidates, depending on their properties and whether they pass the other identification criteria. Photons must be identified, however, for the $t\bar{t}+\gamma$ sample that is used in the data-driven estimation of the $t\bar{t}+Z$ background. In this case, photon candidates are reconstructed from calorimeter cell clusters and are required to pass the ‘Tight’ identification criteria described in Ref. [90]. Furthermore, photons are required to have $p_T > 125 \text{ GeV}$ and $|\eta| < 2.37$ so that the photon trigger is fully efficient. Photons must further pass isolation criteria based on both track and calorimeter information.

Jet candidates are built from topological clusters [91, 92] in the calorimeters using the anti-$k_t$ algorithm with a jet radius parameter $R = 0.4$ [93]. Jets are corrected for contamination from pileup using the jet areas method [94–96] and then calibrated to account for the residual detector response [97, 98]. Jets in data are further calibrated based on in situ measurements of the jet energy scale. Baseline jets are required to have $p_T > 20 \text{ GeV}$. Signal jets must have $p_T > 25 \text{ GeV}$ and reside within $|\eta| < 2.5$. Furthermore, signal jets with $p_T < 50 \text{ GeV}$ are required to pass criteria, implemented in the jet vertex tagger algorithm [96], designed to reject jets originating from pileup. Events containing a jet that does not pass specific jet quality requirements are vetoed from the analysis in order to suppress detector noise and non-collision...
The missing transverse momentum vector is reconstructed from the negative sum of the transverse momenta of baseline electrons, muons, jets, and a soft-term built from tracks not associated to other reconstructed objects [106, 107]. For the event selections requiring photons, the calibrated photon is directly included in the $E_{\text{T}}^{\text{miss}}$ calculation. In all other cases, photons and hadronically decaying $\tau$ are not explicitly included but enter as jets, electrons or via the soft-term.

To avoid labelling the same detector signature as more than one object, an overlap removal procedure is applied. The procedure was tailored for this analysis and optimized using simulation. Table 2 summarizes the procedure. Given the sets of baseline objects, the procedure checks for overlap based on the minimal distance $\Delta R$ between pairs of objects. For example, if a baseline electron and a baseline jet are found with $\Delta R < 0.2$, then the electron is preserved (‘resolution’) and the jet is discarded, unless the jet is $b$-tagged (‘condition’) in which case the electron is assumed to stem from a heavy-flavour decay and is hence discarded while the jet is preserved. The order of the procedure is given by the columns in Table 2 which are executed from left to right. The steps involving a photon are not applied in the main event selection, but only for the event selection where photons are identified. For the remainder of the note, all baseline and signal objects are those that have survived the overlap removal procedure.

Large-radius jets are clustered from all signal (small-radius) jets using the anti-$k_t$ algorithm with $R = 1.0$ or 1.2, and are groomed using re-clustered jet trimming with a $p_T$ fraction of 5% [108–111]. Electrons and muons are not included in the re-clustering, since it was found that including them increases the background acceptance more than the signal efficiency. Large-radius jets are not used in the overlap removal procedure; however, the signal jets that enter the re-clustering have passed the overlap removal.
procedure described above. The analysis also uses a large-radius jet mass, where the squared mass is defined as the square of the four-vector sum of the constituent (small-radius) jets.

All events are required to have $E^\text{miss}_T > 200$ GeV, exactly one signal lepton and no additional baseline leptons, at least four signal jets, have a transverse mass$^7$ of the signal lepton and the missing transverse momentum satisfying $m_T > 30$ GeV, and have an azimuthal angle between leading or sub-leading jet and the missing transverse momentum of $|\Delta\phi(jet, p^\text{miss}_T)| > 0.4$ with $i \in \{1, 2\}$. The $H^{\text{miss}}_{T,\text{sig}}$ variable, based on the identified lepton, jets and the per-event jet energy uncertainties, is also used (more details in Ref. [30, 112]). The latter three criteria suppress multijet processes with mis-identified or non-prompt leptons and mis-measured $E^\text{miss}_T$ to a negligible level. With the above event selection, the dominant backgrounds are $t\bar{t}$ events with at least one leptonically decaying $W$ boson, and $W$+jets production. A powerful technique for suppressing these background processes is to require $m_T$ to be greater than the $W$ boson mass.

Of the residual backgrounds, one of the dominant contributions is $t\bar{t}$ production where both $W$ bosons decay leptonically, or one $W$ boson decays leptonically and the other via a hadronic $\tau$. A series of additional variables, described in detail in Ref. [30], are used to discriminate between this background and the signal processes. The $m^\chi_{\text{top}}$ variable is the invariant mass of the three jets in the event most compatible with coming from a hadronically decaying top quark, and where the three jets are selected by minimizing a $\chi^2$-distribution including the jet momenta and energy resolutions. The asymmetric $m_{T2}$ ($am_{T2}$) [113–116] and $m_{T2}^\tau$ are both variants of the variable $m_{T2}$ [117], a generalization of the transverse mass applied to signatures where two particles are not directly detected. The $am_{T2}$ variable targets dileptonic $t\bar{t}$ events where one lepton is not reconstructed while the $m_{T2}^\tau$ variable targets $t\bar{t}$ events where one of the two $W$ bosons decays via a hadronically decaying $\tau$. The topness [118] variable is based on minimizing a $\chi^2$-type function quantifying the compatibility with a dileptonic $t\bar{t}$ event where one lepton is not reconstructed. Furthermore, the mass of large-radius jets is useful when the boost of the top quark is significant.

An important change from the Run 1 suite of tools is the treatment of hadronically decaying $\tau$ candidates in the $m_{T2}^\tau$ variable. Events are removed if one of the selected jets is additionally identified as a hadronic $\tau$ candidate, and the corresponding $m_{T2}^\tau < 80$ GeV, where $m_{T2}^\tau$ uses the signal lepton and hadronic $\tau$ candidate as the two visible objects. This $\tau$ veto removes approximately 40% of simulated $t\bar{t}$ events where at truth-level one $W$ boson decays leptonically and the other proceeds via a hadronically decaying $\tau$, for an event selection with a $E^\text{miss}_T > 200$ GeV requirement. For the considered signal models, the veto removes 1% of the events and has a negligible impact. The $\tau$ veto is applied in all following event selections except those defining the $t\bar{t} + Z$ control region (since the veto would remove only about 1% of the events in this region).

5 Signal Regions

Three signal event selections (called signal regions, or SR1–3) are constructed using the set of discriminating variables described in the previous Section 4. The three signal regions are optimized before looking at the data to maximize the discovery sensitivity using three benchmark signal models from the gluino-mediated stop models, each representing distinct phenomenology. The benchmark models for SR1 and SR2 are chosen to have production cross-sections and kinematic properties similar to those of direct stop pair production models near the edge of the Run 1 exclusion limit [30, 119], while the benchmark model

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$^7$ The transverse mass, $m_T$, is defined as $m_T^2 = 2p_{T,\text{lep}}^\text{lep} E^\text{miss}_T (1 - \cos(\Delta\phi))$, where $\Delta\phi$ is the azimuthal angle between the lepton and the missing transverse momentum direction. The quantity $p_{T,\text{lep}}^\text{lep}$ is the transverse momentum of the charged lepton.
for SR3 cannot be mapped in these terms to any direct stop model. The SR1–3 target signal models with increasing gluino masses, ranging from 1.1 TeV to 1.4 TeV, respectively, and \( \tilde{t}_1 \) masses between 600 and 800 GeV for SR1–2.

The three signal regions are characterized by increasing \( E_T^{\text{miss}} \) requirements. The SR1 benchmark has the softest \( E_T^{\text{miss}} \) spectrum and the available momentum of the hadronically decaying top quark is typically not sufficient to capture all of the decay products into a single large-radius jet. As a result, the resolved top reconstruction \( m_{\chi_{\text{top}}} \) is useful for rejecting dileptonic \( t\bar{t} \) and other background events without a resonant top quark with hadronic decay products. In contrast, the boost of the hadronically decaying top quarks in the SR2 and SR3 benchmarks is often sufficient to capture all decay products inside a single large-radius jet. The angular separation between the decay products scales with the inverse of the momentum. Therefore, the optimal large-radius jet cone size is found to be larger for SR2 \((R = 1.2)\) than for SR3 \((R = 1.0)\). Additional requirements on \textit{topness} and \textit{am}_{T2} further reduce the dileptonic \( t\bar{t} \) background. Events without a high \( p_T \) top quark that decays leptonically are suppressed by using a requirement on the \( \Delta R \) between the highest \( p_T \) \( b \)-jet and the signal lepton. The regions have additional requirements on \( m_{T1} \) and \( H_T^{\text{miss}} \) to further exploit the large genuine \( E_T^{\text{miss}} \) from undetected neutralinos. A requirement of at least one \( b \)-tagged jet amongst the four highest \( p_T \) jets is used in all SR1–3 in order to reduce the \( W \)+jets and diboson backgrounds.

The signal region definitions are summarized in Table 3 and the expected yields in all three regions are shown in Table 4. The signal regions are not mutually exclusive.

### 6 Background Estimates

The dominant background processes are the production of \( t\bar{t} \) and single top \( Wt \) events where both \( W \) bosons decay leptonically (one of which is ‘lost’, meaning it is either not reconstructed, not identified, or removed by the overlap removal procedure) or one \( W \) boson decays leptonically and the other via a hadronically decaying \( \tau \); \( t\bar{t} + Z(\rightarrow \nu \bar{\nu}) \); and \( W \)+jets. Other background processes considered are semi-leptonic \( t\bar{t} \), dibosons, \( t\bar{t} + W, Z \)+jets and multijet events.

The main background processes are estimated by isolating each of them in a dedicated control region (CR), described in Section 6.1, normalizing simulation to match data in a simultaneous fit. This fit is performed separately for each SR with the associated CRs. The accuracy of the fits is tested in a series of validation regions (VR), discussed in Section 6.2. Figure 2 schematically illustrates the setup for one example SR and its associated CRs and VRs. The CRs for \( Wt \) and \( t\bar{t} + Z \) are new with respect to the Run 1 analysis.

The multijet background is estimated from data using a fake factor method [120]. The contribution is found to be negligible. All other (small) backgrounds are determined entirely from simulation, normalized to the most accurate theoretical cross-sections available. The \( Z \)+jets background is found to be negligible.

#### 6.1 Control Regions

A series of control regions are defined as event selections that are kinematically close to the signal regions but with a few key variable thresholds inverted to significantly reduce signal contamination and enhance
the yield and purity of a particular background. These control regions are then used to constrain the background normalization. Each of the three signal regions has a dedicated control region for the $t\bar{t}$ (TCR), for the $W+$jets (WCR), for the single top (STCR) and for the $t\bar{t}+W/Z$ (TZCR) background processes. The general strategy in constructing the control regions is to invert the transverse mass requirement from a high threshold to a low window. The requirements on several variables are loosened to increase the statistical power of the CR. The details of the TCR and the WCR are described in Section 6.1.1, while the STCR and TZCR are documented in Section 6.1.2 and 6.1.3 respectively. Table 3 presents an overview of the CR selections for the TCR, WCR and STCR corresponding to SR1, SR2, and SR3.

A likelihood fit is performed for each SR involving the SR and the associated CRs [121]. The expected number of events in each region is given by the sum over all background processes, and optionally a signal model. The normalizations of the $t\bar{t}$, $t\bar{t}+W/Z$, single top, and $W+$jets backgrounds are controlled by four free parameters (normalization factors, NFs) in the fit. The electron and muon channels are always added together. To obtain a set of background predictions that is independent of the observation in the SRs, the fit can be configured to use only the CRs to constrain the fit parameters: the SR bins are removed from the likelihood and any potential signal contribution is neglected everywhere. This fit configuration is referred to as the background-only fit.

Figure 2: A schematic diagram for the various event selections used to estimate and validate the background model and then search for stop production. Solid lines indicate kinematic boundaries while dashed lines indicate that the events can extend beyond the boundary. CR, VR, and SR stand for control region, validation region, and signal region, respectively. T, ST, TZ, and W stand for $t\bar{t}$, single top, $t\bar{t}+Z$, and $W+$jets, respectively.
Common event selection

<table>
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<th>Variable</th>
<th>SR1</th>
<th>TCR1 / WCR1</th>
<th>STCR1</th>
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<td>&gt; 200</td>
<td>&gt; 200</td>
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<tr>
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<td>&gt; 5</td>
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<td>[30,90]</td>
<td>[30,120]</td>
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<td>$a_{MT_2}$ [GeV]</td>
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<td>[100,200]</td>
<td>&gt; 100</td>
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<td>–</td>
</tr>
<tr>
<td>$\Delta R(b_1,b_2)$</td>
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Table 3: Overview of the event selections for all SRs and the associated $t\bar{t}$ (TCR), $W+$jets (WCR), and $Wt$ (STCR) control regions. Round brackets are used to describe lists of values and square brackets denote intervals.
6.1.1 Top and W CRs

The TCRs and WCRs are constructed by modifying the $m_T$ selection in the SRs to be a window whose upper edge is near the $W$ boson mass. An additional upper requirement on $am_{T2}$ is applied to the TCRs in order to make them orthogonal to the STCRs, described in the next section. Furthermore, some other kinematic requirements are relaxed or removed to increase the event yields in the CRs. The resulting selections yield 238, 102, and 121 events in TCR1, TCR2, and TCR3, respectively, which are enriched in semi-leptonic $t\bar{t}$ events with purities that vary between 75% and 85%. The WCRs are built from the TCRs by changing the $b$-jet requirement to a $b$-jet veto, and relaxing the $am_{T2}$ requirement. The $b$-jet veto suppresses $t\bar{t}$ events and results in a $W$+jets purity of approximately 75% in all three regions. The selections yield 558, 135, and 352 events in WCR1, WCR2, and WCR3, respectively.

6.1.2 Single Top CR

All of the expected single top contributions in the three SRs are in the $Wt$ channel. This process can evade kinematic bounds from selections targeting the suppression of $t\bar{t}$. Nonetheless, isolating a pure sample of $Wt$ events kinematically close to the SRs is challenging due to the similarity of $Wt$ and $t\bar{t}$. The $Wt$ events that pass signal region-like event selections often have a second $b$-jet within acceptance. The $am_{T2}$ variable is useful for discriminating $t\bar{t}$ and $Wt$ because the mass of the $Wb$ system not from the resonant top quark is typically higher than for an on-shell top quark in the phase space selected by this analysis. Therefore, the STCRs are characterized by $am_{T2} > 200$ GeV. Furthermore, to increase the purity of $Wt$ and reduce the $W$+jets contamination, events are required to have two $b$-tagged jets. Top quark pair events often exceed the $am_{T2}$ kinematic bound when one of the two $b$-tags used in the $am_{T2}$ calculation is a jet produced from a charm quark from the $W$ decay. When this jet is from the same top quark as the other $b$-tagged jet then the $\Delta R$ between them tends to be smaller than for $Wt$ events that have two $b$-jets from $b$-quarks that are naturally well separated. Therefore, to further increase the $Wt$ purity, events in the STCRs are required to have $\Delta R(b_1, b_2) > 1.2$ where $b_1$ and $b_2$ are the two highest $p_T$ $b$-tagged jets. Figure 3 shows distributions of the defining variables for STCR1 with all requirements applied but the one plotted. The expected purity for $Wt$ events is approximately 40% in all three STCRs, and the selections yield 62, 71, and 45 events in STCR1, STCR2, and STCR3, respectively.

6.1.3 $t\bar{t} + Z$ CR

Top quark pair production in association with a $Z$ boson that decays into neutrinos is an irreducible background. The expected contributions of $t\bar{t} + W$ in the three SRs are less than 10% with respect to the expected $t\bar{t} + Z$ yields, and the two processes are lumped together in the analysis. A CR using charged leptonic $Z$ boson decays is not feasible given the small branching fraction to leptons and the limited dataset available. However, a data-driven approach is still possible using a similar process: $t\bar{t} + \gamma$. Similar techniques have been used for estimating $Z(\rightarrow \nu\bar{\nu})+\text{jets}$ from $\gamma+\text{jets}$ [122] and the method was studied as a VR using the Run 1 data [30]. An event selection is constructed requiring a high $p_T$ photon that is then treated as $E_T^{\text{miss}}$ in direct analogy to $Z \rightarrow \nu\bar{\nu}$.

The CR is designed to minimize the differences between the two processes, in order to reduce the theoretical uncertainties in the extrapolation. The Feynman diagrams in the ME expansion for the production of $t\bar{t} + Z$ and $t\bar{t} + \gamma$ are identical, except for a negligible contribution from the coupling of the $Z$ boson to neutrinos that is absent for photons. The main differences arise from the $Z$ boson mass, which reduces
Figure 3: Comparison of data with estimated backgrounds in the $am_{T2}$ (top left), $b$-tagged jet multiplicity (top right), and $\Delta R(b_1, b_2)$ distributions with the STCR1 event selection except for the requirement (indicated by an arrow) of the variable shown. Furthermore, the $\Delta R(b_1, b_2)$ requirement is dropped in the shown $b$-tagged jet multiplicity distribution. The predicted backgrounds are scaled with the NFs documented in Table 4. The uncertainty band includes statistical and all experimental systematic uncertainties. The last bin includes overflow. The middle panel shows the ratio of the data yield to the SM prediction, while the lower panel shows the ratio of the single top yield to either the $t\bar{t}$ prediction (top left and bottom) or the $W+$jets prediction (top right).
the available phase space causing differences in kinematic distributions. In addition, the bremsstrahlung rate for Z bosons is highly suppressed at LHC energies, while there is a large contribution to the $t\bar{t}$ + $\gamma$ cross-section from photons radiating from the top quark and its decay products. Both of these differences are mitigated if the boson $p_T$ is larger than the Z boson mass. In this limit, the impact of the mass difference on the available phase space is reduced and the rate of photon radiation from bremsstrahlung is suppressed [83]. In high $E_T^{\text{miss}}$ $t\bar{t}$ + $Z(\rightarrow \nu\bar{\nu})$ events, the Z boson $p_T$ is the dominant source of $E_T^{\text{miss}}$ and so most $t\bar{t}$ + $Z$ events in the SRs have large $Z p_T$.

Two $t\bar{t}$ + $\gamma$ CRs are designed to be kinematically close to SR1 and SR2/SR3. Both regions require at least one signal photon, exactly one signal lepton and no additional baseline leptons, and at least four signal jets from which at least one must be $b$-tagged. The two regions have the same jet $p_T$ thresholds as the corresponding signal regions. To mimic the $Z \rightarrow \nu\bar{\nu}$ decay, the highest $p_T$ photon is vectorially added to $p_T^{\text{miss}}$ which is used to construct $E_T^{\text{miss}} = |p_T^{\text{miss}} + p_T^{\gamma}|$, $m_T$ and $H_T^{\text{miss}}$. Events entering the TZCRs are required to satisfy $E_T^{\text{miss}} > 120$ GeV, $m_T > 100$ GeV and $H_T^{\text{miss}} > 5$ in order to bring the region kinematically closer to the SRs. Finally, $E_T^{\text{miss}} < 200$ GeV is imposed to ensure orthogonality between the TZCR and the other CRs and SRs. The resulting regions have over 90% $t\bar{t}$ + $\gamma$ purity, and yield 43 and 45 events in TZCR1, TZCR2 (=TZCR3), respectively. Figure 4 shows the distribution of $E_T^{\text{miss}}$ and $m_T$ in the TZCR1 corresponding to SR1 before the requirement on the plotted variable is applied. The contribution from events not involving top quarks is negligible. The total number of events in data is about 40% higher than in simulation, but there is no significant evidence for mis-modeling of the shapes of the various distributions within uncertainties.

Figure 4: Comparison of data with estimated backgrounds in the $E_T^{\text{miss}}$ and $m_T$ distributions with the TZCR1 event selection except for the requirement (indicated by an arrow) of the shown variable. The variables $E_T^{\text{miss}}$ and $m_T$ are constructed in the same way as $E_T^{\text{miss}}$ and $m_T$ but treating the leading photon transverse momentum as invisible. The predicted backgrounds are scaled with the NFs documented in Table 4. The uncertainty band includes statistical and all experimental systematic uncertainties. The last bin includes overflow.
Figure 5: Comparison of the observed data ($n_{\text{obs}}$) with the predicted background ($n_{\text{exp}}$) in the validation and signal regions. The background predictions are obtained using the background-only fit configuration. The bottom panel shows the significance of the difference between data and predicted background, where the significance is based on the total uncertainty ($\sigma_{\text{tot}}$).

### 6.2 Validation Regions

The background estimates are tested using validation regions, which are disjoint to both control and signal regions. Background normalizations determined in the control regions are extrapolated to the VRs and compared with the observed data. Each signal region has associated validation regions for the $t\bar{t}$ (TVR) and $W+$jets (WVR) processes that are constructed with the same selection as the TCR/WCR except that $m_T$ is between 90 and 120 GeV. The validation regions are not used to constrain parameters in the fit, but provide a statistically independent test of the background estimates using the CRs. In Fig. 5, background estimates in all the associated VRs are compared to the observed data. The potential signal contamination in the VRs is studied for all considered signal models (and SUSY mass ranges) and found to be negligible.

A second set of validation regions, not associated with any of the three signal regions, is used for general monitoring purposes. Some of the dominant backgrounds are dileptonic $t\bar{t}$ and lepton-hadronic $\tau$ $t\bar{t}$ events. To pass the four-jet requirement, such events must have at least one hard jet that does not originate

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Footnote: A $Wt$ VR is not defined since the $m_T$ range in the STCR is extended up to 120 GeV to increase the statistics.
Figure 6: Jet multiplicity distributions for events where exactly two signal leptons (left) or one lepton plus one \( \tau \) candidate (right) are selected. No correction factors are included in the background normalizations. The uncertainty band includes statistical and all experimental systematic uncertainties. The last bin includes overflow.

from the \( t\bar{t} \) decay (two hard jets for dileptonic \( t\bar{t} \)). The modeling of these extra jets is validated in dedicated VRs that require either two signal leptons (electron or muon) or one signal lepton and one hadronic \( \tau \) candidate. In Fig. 6 the jet multiplicity distributions are shown for event selections of an electron-muon pair (left) and one lepton plus one \( \tau \) candidate (right). Additional validation regions are constructed by considering (1) events with high \( E_{\text{miss}} \), high \( m_T \) and low \( a_{mT2} \) for dilepton \( t\bar{t} \) events with a lost lepton or (2) high \( m_T \) and a \( b \)-jet veto to probe the modeling of the resolution-induced \( m_T \) tail in \( W+\)jets events (using the WVR-tail region in Fig. 2). There are no significant indications of mis-modeling in any of the validation regions.

7 Systematic Uncertainties

The systematic uncertainties on the signal and background estimates arise both from experimental sources and from the uncertainties in the theoretical predictions and modelling. Since the yields for the dominant background sources, \( t\bar{t} \), single top, \( t\bar{t}V \) and \( W+\)jets, are all obtained in dedicated control regions, the modelling uncertainties for these processes affect only the extrapolation from the CRs into the signal regions (and between the various control regions), but not the overall normalization. The systematic uncertainties are included as nuisance parameters with Gaussian constraints and profiled in the likelihood fits.

The dominant experimental uncertainties arise from imperfect knowledge of the jet energy scale (JES) and jet energy resolution (JER) [98], the modelling of the \( b \)-tagging efficiencies for \( b \), \( c \) and light-flavour jets [123, 124] as well as the contribution to the \( E_{\text{miss}} \) soft-term i.e. from tracks not associated with any reconstructed objects and from pileup. The resulting uncertainties from these sources on the extrapolation factors from the four CRs to the SRs are 4–15\% for JES, 0–9\% for JER, 0–6\% for \( b \)-tagging, and 0–3\% for the \( E_{\text{miss}} \) soft-term. Other sources of experimental uncertainties are the modelling of lepton- and photon-related quantities (energy scales, resolutions, reconstruction and identification efficiencies,
The SUSY signal cross-section uncertainty is taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in Ref. [127], and the
resulting uncertainties range from 13% to 23%. The uncertainty on the VLQ signal cross-section is 10% [76].

8 Results

Table 4 (top part) and Fig. 5 (right part) show the number of observed events together with the predicted number of background events in the three SRs. The prediction is obtained using the background-only fit configuration described in Section 6. The SR2 and SR3 predicted yields agree well with the observed data in those regions. Table 4 (middle part) also lists the results of the four free fit parameters that control the normalization of the four main backgrounds (normalization factors, NFs), together with the associated fit uncertainties. To quantify the compatibility of the SM background-only hypothesis with the observations in the SRs, a profile likelihood ratio test is performed. These fits are configured to include the SR bin in the likelihood. Table 4 also reports the resulting \( p \)-values \( (p_0) \), which are set to 0.5 for SR2 and SR3 as the observation lies below the prediction. The data exceeds the background prediction in SR1 by 2.3 standard deviations. Figure 7 shows the \( E_{\text{miss}} \) and \( m_T \) distributions in SR1 for the data, for the background prediction, as well as for two representative signal models.

The data are used to derive one-sided limits at 95% CL on generic beyond-SM yields and on the considered signal models. The results are obtained from a profile likelihood ratio test following the CLs prescription [128]. Model-independent upper limits on beyond-SM contributions are derived separately for each SR, where the fit is configured to include the SR and all its associated CRs. A generic signal model is assumed that contributes only to the SR and for which neither experimental nor theoretical systematic uncertainties except for the luminosity uncertainty are considered. The resulting limits, expected as well as observed, on the number of beyond-SM events are shown in the bottom rows of Table 4.

Exclusion limits are also derived for the gluino-mediated stop and direct stop pair production models. The signal uncertainties and potential signal contributions to all regions are taken into account. All uncertainties except those on the theoretical signal cross-section are included in the fit. Combined exclusion
limits are obtained by selecting a priori the signal region with the lowest expected CL$_s$ value for each signal model.

Figure 8 shows the expected and observed exclusion contours for both gluino-mediated and direct pair production of stops. The ±1 $\sigma_{\text{exp}}$ (yellow) uncertainty band indicates the impact on the expected limit of all uncertainties included in the fit. The ±1 $\sigma_{\text{th}}$ (dotted red) uncertainty lines around the observed limit illustrate the change in the observed limit as the nominal signal cross-section is scaled up and down by the theoretical cross-section uncertainty. The gap in the observed exclusion between around 600 and 750 GeV in the direct stop model is due to the transition of signal regions (SR1 has the best expected sensitivity up to around 750 GeV for a massless $\tilde{\chi}_1^0$, beyond that SR2 has the best sensitivity) and the excess observed in SR1. The limits are sensitive to signal model assumptions. The gluino-mediated models have a 5 GeV mass splitting between the stop and the neutralino and 100% branching ratio $\tilde{t} \rightarrow c + \tilde{\chi}_1^0$. The impact of varying both of these assumptions is studied for SR2 with a benchmark model characterized by masses for the gluino and the stop of $(m_{\tilde{g}}, m_{\tilde{t}_1}) = (1250, 750)$ GeV. There is a small increase in the CL$_s$ value when increasing the mass gap from 5 to 20 GeV and from switching between the two-body stop decay and the four-body stop decay $\tilde{t} \rightarrow b f f^* \tilde{\chi}_1^0$, each with 100% branching ratio, but under all of these variations the model is excluded. The direct stop pair production limits depend on the mixing of $\tilde{t}_L$ and $\tilde{t}_R$ in forming the mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$. The nominal results assume that the $\tilde{t}_1$ is mostly the $\tilde{t}_R$. The stop mass limit for a massless neutralino is approximately 70 GeV weaker when the $\tilde{t}_1$ is the $\tilde{t}_L$.

The search for direct gluino and direct stop production can also be used to set limits on other models of physics beyond the SM that produce $t\bar{t} + E_T^{\text{miss}}$. Examples are third generation leptoquarks [129–135], which decay into a top quark and a neutrino ($L_Q \rightarrow tv$), and VLQ ($T$) models. For the former, limits
on scalar $LQ \to t\nu$ are identical to limits on direct stop pair production with a massless neutralino and unpolarized top quarks. For the latter, simulated samples of pair produced $T$ are used to re-interpret the results. The $T$ is assumed to decay in three possible ways: $T \to tZ, T \to tH$, and $T \to bW$. The direct $T$ pair production cross-section is higher than for stops due to additional spin states, but after accounting for the $Z (\to \nu\bar{\nu})$ branching ratio, the models have a similar predicted yield. For a $T$ quark with mass 800 GeV (just beyond the Run 1 limit [136, 137]), a branching ratio $B (T \to tZ)$ above 90% is excluded.

**9 Conclusion**

This document presents a search for pair production of gluino-mediated stops with a small mass splitting between the stop and the LSP, and direct pair production of stops in final states with one isolated lepton, jets, and missing transverse momentum. Three signal region selections are optimized for discovering benchmark models just beyond the exclusion limits of LHC Run 1 from searches with the same $t\bar{t} + E_{T}^{miss}$ signature. The search uses 3.2 fb$^{-1}$ of LHC data collected by the ATLAS experiment at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The observed data are consistent with data-driven background estimates in all three regions. The largest difference between data and the corresponding prediction is in the most inclusive signal region (SR1) and corresponds to 2.3 standard deviations above the estimated background. In the absence of a significant excess, exclusion limits at 95% CL are derived on the target gluino and stop pair production models. These extend the LHC Run 1 exclusion limits on the gluino mass up to 1460 GeV in the gluino-mediated stop pair production model in the high gluino and low stop mass region, and also add an excluded stop mass region from 745 to 780 GeV in the model of stop pair production with a massless lightest neutralino.
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