**THE EUROPEAN
PHYSICAL JOURNAL C**

CrossMark

ORIGINAL PAPER

Search for gluinos in events with an isolated lepton, jets and missing transverse momentum at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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Abstract The results of a search for gluinos in final states with an isolated electron or muon, multiple jets and large missing transverse momentum using proton–proton collision data at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV are presented. The dataset used was recorded in 2015 by the ATLAS experiment at the Large Hadron Collider and corresponds to an integrated luminosity of 3.2 fb^{-1}. Six signal selections are defined that best exploit the signal characteristics. The data agree with the Standard Model background expectation in all six signal selections, and the largest deviation is a 2.1 standard deviation excess. The results are interpreted in a simplified model where pair-produced gluinos decay via the lightest chargino to the lightest neutralino. In this model, gluinos are excluded up to masses of approximately 1.6 TeV depending on the mass spectrum of the simplified model, thus surpassing the limits of previous searches.

1 Introduction

Supersymmetry (SUSY) [1–6] is a theoretical framework of physics beyond the Standard Model (SM) that predicts for each SM particle the existence of a supersymmetric partner differing by half a unit of spin. The partner particles of the SM fermions (quarks and leptons) are the scalar squarks ($\tilde{q}$) and sleptons ($\tilde{\ell}$). In the boson sector, the supersymmetric partner of the gluon is the fermionic gluino ($\tilde{g}$), whereas the supersymmetric partners of the Higgs (higgsinos) and the electroweak gauge bosons (winos and bino) mix to form charged and neutral mass eigenstates called charginos ($\tilde{\chi}_{1,2}^{\pm}$) and neutralinos ($\tilde{\chi}_{1,2,3,4}^{0}$). In the Minimal Supersymmetric extension of the Standard Model (MSSM) [7,8] two scalar Higgs doublets along with their Higgsino partners are predicted. SUSY addresses the SM hierarchy problem [9–12] provided that the masses of at least some of the supersymmetric particles (most notably the higgsinos, the top squarks and the gluinos) are near the TeV scale.

In R-parity-conserving SUSY [13], gluinos might be pair-produced at the Large Hadron Collider (LHC) via the strong interaction and decay either directly or via intermediate states to the lightest supersymmetric particle (LSP). The LSP is stable and is assumed to be only weakly interacting, making it a candidate for dark matter [14,15].

This paper considers a SUSY-inspired model where pair-produced gluinos decay via the lightest chargino ($\tilde{\chi}_{1}^{\pm}$) to the LSP, which is assumed to be the lightest neutralino ($\tilde{\chi}_{1}^{0}$). The three-body decay of the gluino to the chargino proceeds via $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_{1}^{\pm}$. The chargino decays to the LSP by emitting an on- or off-shell W boson, depending on the available phase space. In the MSSM this decay chain is realised when the gluino decays via a virtual squark that is the partner of the left-handed SM quark, to the chargino with a dominant wino component. In the MSSM the mass of the chargino is independent of the mass of the gluino.

The experimental signature characterising this search consists of a lepton (electron or muon), several jets, and missing transverse momentum ($\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}$ with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) from the undetectable neutralinos and neutrino(s). The analysis is based on two complementary sets of search channels. The first set requires a low transverse momentum (p_{T}) lepton ($7/6 < p_{\mathrm{T}}(e/\mu) < 35$ GeV), and is referred to as the soft-lepton channel, while the second set requires a high-p_{T} lepton ($p_{\mathrm{T}}(e/\mu) > 35$ GeV) and is referred to as the hard-lepton channel. The two sets target SUSY models with small and large mass differences between the predicted supersymmetric particles, respectively. The search uses the ATLAS data collected in proton–proton LHC collisions in 2015 corresponding to an integrated luminosity of 3.2 fb^{-1} at a centre-of-mass energy of 13 TeV.

The analysis extends previous ATLAS searches with similar event selections [16] which were performed with data collected during the first data-taking campaign between 2010
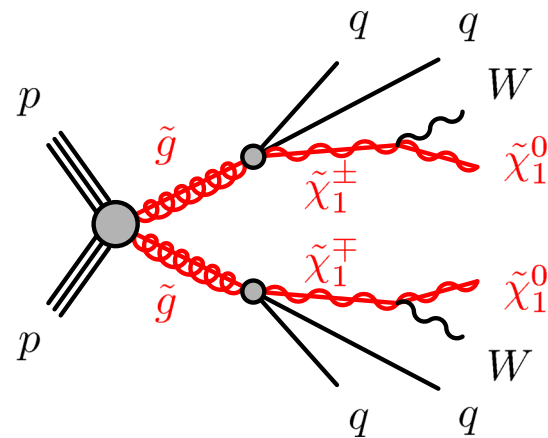
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and 2012 (LHC Run 1) at a centre-of-mass energy of up to 8 TeV. The results of all Run 1 ATLAS searches targeting squark and gluino pair production are summarised in Ref. [17]. The CMS Collaboration has performed similar searches for gluinos with decays via intermediate supersymmetric particles in Run 1 [18,19] and Run 2 [20].

This paper is structured as follows. After a brief description of the ATLAS detector in Sect. 2, the simulated data samples for the background and signal processes used in the analysis as well as the dataset and the trigger strategy are detailed in Sect. 3. The reconstructed objects and quantities used in the analysis are described in Sect. 4 and the event selection is presented in Sect. 5. The background estimation and the systematic uncertainties associated with the expected event yields are discussed in Sects. 6 and 7, respectively, while details of the statistical interpretation are given in Sect. 8. Finally, the results of the analysis are presented in Sect. 9 and are followed by a conclusion.

2 ATLAS detector

ATLAS [21] is a general-purpose detector with a forward-backward symmetric design that provides almost full solid angle coverage around the interaction point.[1] The main components of ATLAS are the inner detector (ID), which is surrounded by a superconducting solenoid providing a 2 T axial magnetic field, the calorimeter system, and the muon spectrometer (MS), which is immersed in a magnetic field generated by three large superconducting toroidal magnets. The ID provides track reconstruction within $|\eta| < 2.5$, employing pixel detectors close to the beam pipe, silicon microstrip detectors at intermediate radii, and a straw-tube tracker with particle identification capabilities based on transition radiation at radii up to 1080 mm. The innermost pixel detector layer, the insertable B-layer [22], was added during the shutdown between LHC Run 1 and Run 2, at a radius of 33 mm around a new, narrower, beam pipe. The calorimeters cover $|\eta| < 4.9$, the forward region $(3.2 < |\eta| < 4.9)$ being instrumented with a liquid-argon (LAr) calorimeter for both the electromagnetic and the hadronic measurements. In the central region, a lead/LAr electromagnetic calorimeter covers $|\eta| < 3.2$, while the hadronic calorimeter uses two different detector technologies, with scintillator tiles ($|\eta| < 1.7$) or

Fig. 1 The decay topology of the signal model considered in this search

LAr ($1.5 < |\eta| < 3.2$) as the active medium. The MS consists of three layers of precision tracking chambers providing coverage over $|\eta| < 2.7$, while dedicated fast chambers allow triggering over $|\eta| < 2.4$. The ATLAS trigger system (developed from Ref. [23]) consists of a hardware-based first-level trigger and a software-based high-level trigger.

3 Simulated event samples and data samples

The signal model considered in this search is a simplified model [24–26] that has been used in previous similar ATLAS searches [16]. In this model, exclusive pair-production of gluinos is assumed. The gluinos decay via an intermediate chargino, here the lightest chargino $\tilde{\chi}_1^\pm$, into the lightest supersymmetric particle, the lightest neutralino $\tilde{\chi}_1^0$. The branching ratio of each supersymmetric particle decay considered is assumed to be 100 %. Other supersymmetric particles not entering the decay chain described are not considered in this simplified model and their masses are set to high values. The gluino decay is assumed to proceed only via virtual first- and second- generation quarks, hence no bottom or top quarks are produced in the simplified model. The free parameters of the model are the masses of the gluino ($m_{\tilde{g}}$), the chargino ($m_{\tilde{\chi}_1^\pm}$), and the neutralino ($m_{\tilde{\chi}_1^0}$). Two types of scenarios are considered: in the first type, the mass of the neutralino is fixed to 60 GeV, and the sensitivity is assessed as a function of the gluino mass and a mass-ratio parameter defined as $x = (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})/(m_{\tilde{g}} - m_{\tilde{\chi}_1^0})$. In the second type, $m_{\tilde{g}}$ and $m_{\tilde{\chi}_1^0}$ are free parameters, while $m_{\tilde{\chi}_1^\pm}$ is set to $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{g}} + m_{\tilde{\chi}_1^0})/2$. The decay topology of the simplified model is illustrated in Fig. 1.

The signal samples are generated using MG5_AMC@NLO 2.2.2 [27] with up to two extra partons in the matrix element, interfaced to PYTHIA 8.186 [28] for parton showers and hadronisation. For the combination of the

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and the rapidity is defined as $y = 0.5\ln[(E + p_z)/(E - p_z)]$, where E is the energy and p_z the longitudinal momentum of the object of interest.

matrix element and the parton shower the CKKW-L matching scheme [29] is applied with a scale parameter that is set to a quarter of the mass of the gluino. The ATLAS A14 [30] set of tuned parameters (tune) for the underlying event is used together with the NNPDF2.3 LO [31] parton distribution function (PDF) set. The EvtGen v1.2.0 program [32] is used to describe the properties of the bottom and charm hadron decays in the signal samples.

The signal cross-sections are calculated at next-to-leading order (NLO) in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLL) [33–37]. The nominal cross-section and its uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales [38,39].

The simulated event samples for the SM backgrounds are summarised in Table 1, along with the PDFs and tunes used. Further samples are also used to assess systematic uncertainties, as explained in Sect. 7.

For the production of $t\bar{t}$ and single top quarks in the Wt and s-channel [43] the POWHEG- BOX v2 [44] generator with the CT10 [45] PDF sets in the matrix-element calculations is used. Electroweak t-channel single-top-quark events are generated using the POWHEG- BOX v1 generator. This generator uses the four-flavour scheme for the NLO matrix-element calculations together with the fixed four-flavour PDF set CT10f4. For all top-quark processes, top-quark spin correlations are preserved (for the single-top t-channel, top quarks are decayed using MadSpin [46]). The parton shower, fragmentation and the underlying event are simulated using PYTHIA 6.428 with the CTEQ6L1 [47] PDF set and the corresponding PERUGIA2012 tune (P2012) [42]. The top-quark mass is assumed to be 172.5 GeV. The $t\bar{t}$ events are normalised to the NNLO+NNLL cross-sections. The single-top-quark events are normalised to the NLO cross-sections.

Events containing W or Z bosons with associated jets (W/Z+jets) [48] are simulated using the SHERPA 2.1.1 generator with massive b/c-quarks. Matrix elements are calculated for up to two partons at NLO and four partons at leading order (LO). The matrix elements are calculated using the Comix [49] and OpenLoops [50] generators and merged with the SHERPA 2.1.1 parton shower [51] using the ME+PS@NLO prescription [52]. The CT10 PDF set is used in conjunction with a dedicated parton-shower tuning developed by the SHERPA authors. The W/Z+jets events are normalised to their NNLO cross-sections [53].

The diboson samples [54] are generated with the same generator and PDF setup as the W/Z+jets samples described above. The diboson processes are simulated including final states with four charged leptons, three charged leptons and one neutrino, two charged leptons and two neutrinos, and one charged lepton and three neutrinos. The matrix elements contain all diagrams with four electroweak vertices. They are

Table 1 Simulated background event samples: the corresponding generator, parton shower, cross-section normalisation, PDF set and underlying-event tune are shown

Physics process	Generator	Parton shower	Cross-section normalisation	PDF set	Tune
$W(\to \ell\nu)$ + jets	SHERPA 2.1.1 [40]	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$Z/\gamma^*(\to \ell\ell)$ + jets	SHERPA 2.1.1	SHERPA 2.1.1	NNLO	NLO CT10	SHERPA default
$t\bar{t}$	POWHEG- BOX v2	PYTHIA 6.428 [41]	NNLO+NNLL	NLO CT10	PERUGIA2012 [42]
Single-top (t-channel)	POWHEG- BOX v1	PYTHIA 6.428	NLO	NLO CT10f4	PERUGIA2012
Single-top (s- and Wt-channel)	POWHEG- BOX v2	PYTHIA 6.428	NLO	NLO CT10	PERUGIA2012
$t\bar{t} + W/Z/WW$	MG5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO	NNPDF2.3LO	A14
WW, WZ and ZZ	SHERPA 2.1.1	SHERPA 2.1.1	NLO	NLO CT10	SHERPA default

calculated for up to one parton (4ℓ, $2\ell+2\nu$) or no additional partons ($3\ell+1\nu$, $1\ell+3\nu$) at NLO and up to three partons at LO. The diboson cross-sections are taken from the NLO generator used.

For the $t\bar{t} + W/Z/WW$ processes [55], all events are simulated using MG5_AMC@NLO 2.2.2 at LO interfaced to the PYTHIA 8.186 parton-shower model, with up to two ($t\bar{t} + W$), one ($t\bar{t}+Z$) or no ($t\bar{t}+WW$) extra partons included in the matrix element. The ATLAS underlying-event tune A14 is used together with the NNPDF2.3 LO PDF set. The events are normalised to their respective NLO cross-sections [56,57].

The response of the detector to particles is modelled with a full ATLAS detector simulation [58] using GEANT4 [59], or using a fast simulation [60] based on a parameterisation of the performance of the electromagnetic and hadronic calorimeters and on GEANT4 elsewhere. All background (signal) samples are prepared using the full (fast) detector simulation.

All simulated samples are generated with a varying number of minimum-bias interactions (simulated using PYTHIA 8 with the MSTW2008LO PDF set [61] and the A2 tune [62]) overlaid on the hard-scattering event to model the multiple proton–proton interactions in the same and the nearby bunch crossings. Corrections are applied to the simulated samples to account for differences between data and simulation for trigger, identification and reconstruction efficiencies.

The proton–proton data analysed in this paper were collected by ATLAS in 2015 at a centre-of-mass energy of 13 TeV. During this period the instantaneous luminosity of the LHC reached 5.0×10^{33} cm^{-2} s^{-1} with a mean number of additional pp interactions per bunch crossing of approximately 14. After application of data-quality requirements related to the beam and detector conditions, the total integrated luminosity amounts to 3.2 fb^{-1}, with an associated uncertainty of ± 5 %. These values are derived following the same methodology as the one detailed in Ref. [63].

The data are collected using an E_T^{miss} trigger with a threshold of 70 GeV. This trigger is close to fully efficient after applying the requirement on the offline E_T^{miss} to be larger than 200 GeV.

4 Object reconstruction and identification

The reconstructed primary vertex of an event is required to be consistent with the interaction region and to have at least two associated tracks with $p_T > 400$ MeV. When more than one such vertex is found, the vertex with the largest $\sum p_T^2$ of the associated tracks is chosen.

In the analysis, a distinction is made between preselected reconstructed objects, which fulfil a set of basic criteria and are used in the E_T^{miss} computation, and signal objects that enter the various control, validation and signal regions and are subject to more stringent requirements.

Jets are reconstructed from topological clusters in the calorimeters using the anti-k_t algorithm with a radius parameter $R = 0.4$ [64,65]. Prior to jet reconstruction, clusters are calibrated to the electromagnetic scale response. Additional correction factors derived from simulation and data are applied to the measured jet energy to calibrate it to the particle level [65]. To mitigate the contributions from pile-up, the median energy density of all the jets in the event, multiplied by the jet area, is subtracted from the reconstructed jet energy [66,67]. Preselected jets are required to have $p_T > 20$ GeV and $|\eta| < 4.5$. The contamination from cosmic rays, other sources of non-collision background and detector noise is suppressed using dedicated jet-quality criteria [68]: when such criteria are not fulfilled, the event is rejected.

Electron candidates are reconstructed using ID tracks matched to energy clusters in the electromagnetic calorimeter. They are identified according to the likelihood-based *loose* criteria [69]. Preselected electrons in the soft-lepton (hard-lepton) channel must satisfy $p_T > 7(10)$ GeV and $|\eta| < 2.47$. When the angular separation $\Delta R = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$ between an electron candidate and a preselected jet amounts to $0.2 < \Delta R(e, \text{jet}) < 0.4$, the jet is retained and the electron is rejected to remove electrons originating from b-hadron decays. Since all electrons are also reconstructed as jets, if $\Delta R(e, \text{jet}) < 0.2$ the electron is kept and the jet is discarded. Finally, electron candidates with a $\Delta R(e, \mu) < 0.01$ with respect to a preselected muon (defined below) are rejected and the muon is kept to suppress the contribution of electron candidates from muon bremsstrahlung and subsequent photon conversion.

Muon candidates are reconstructed by combining tracks formed in the ID and the MS sub-systems. The *medium* identification criteria are applied, which offer good efficiency and purity for the selected muons [70]. Preselected muons in the soft-lepton (hard-lepton) channel are required to have $p_T > 6(10)$ GeV and $|\eta| < 2.4$. Muons with an angular separation of $\Delta R(\mu, \text{jet}) < 0.4$ with respect to the closest preselected jet are rejected, after the electron–jet overlap ambiguities are resolved. However, if the number of tracks with $p_T > 500$ MeV associated with the jet is less than three the jet is discarded and the muon kept.

The E_T^{miss} is calculated as the magnitude of the negative vector sum of the transverse momenta of identified and calibrated muons, electrons, jets and photons, in addition to the soft-track term. The soft-track term is defined as the vectorial sum of the p_T of all reconstructed tracks associated with the primary vertex that are not associated with the identified objects entering explicitly the E_T^{miss} computation [71,72].

Signal jets are required to have $p_T > 25$ GeV and $|\eta| < 2.8$. A likelihood discriminant, the jet-vertex tagger (JVT), is used to remove the residual contamination of pile-up jets. The JVT is constructed from track-based variables that are

sensitive to the vertex of origin of the jet [73]. Jets with $p_T < 50$ GeV, $|\eta| < 2.4$ and JVT score less than 0.64 are rejected.

Signal jets containing b-hadrons are identified using the MV2c20 algorithm [74] and are hereafter referred to as b-tagged jets. The MV2c20 algorithm uses as input the impact parameters of all associated tracks and any reconstructed secondary vertex. The requirement chosen in the analysis provides an inclusive b-tagging efficiency of 77 % in simulated $t\bar{t}$ events, along with a rejection factor of 140 for gluon and light-quark jets and of 4.5 for charm jets [74,75].

Signal muons and electrons in the soft-lepton and hard-lepton channels are subject to an additional $p_T < 35$ GeV or $p_T \geq 35$ GeV requirement, respectively. Electrons must satisfy likelihood-based *tight* criteria which are defined in Ref. [69]. In both channels, signal leptons must satisfy the GradientLoose [70] isolation requirements, which rely on the use of tracking-based and calorimeter-based variables and implement a set of η- and p_T-dependent criteria. The efficiency for prompt leptons with transverse momentum < 40 GeV to satisfy the GradientLoose requirements is measured to be about 95 % in $Z \to \ell\ell$ events, progressively rising up to 99 % at 100 GeV [70].

To enforce compatibility with the primary vertex, the distance $|z_0 \cdot \sin(\theta)|$ is required to be less than 0.5 mm for signal lepton tracks, where z_0 is the longitudinal impact parameter with respect to the primary-vertex position. Moreover, in the transverse plane the distance of closest approach of the lepton track to the proton beam line, divided by the corresponding uncertainty, must be less than three for muons and less than five for electrons.

Reconstruction, identification and isolation efficiencies in simulation, when applicable, are calibrated to data for all reconstructed objects.

5 Event selection

Events selected by the trigger are further required to have a reconstructed primary vertex. An event is rejected if it contains a preselected jet which fails to satisfy the quality criteria designed to suppress non-collision backgrounds and detector noise [68]. Exactly one signal lepton is required in both the soft- and the hard-lepton channels. Any event with additional preselected leptons is vetoed to suppress the dilepton $t\bar{t}$, single-top (Wt-channel) and diboson backgrounds.

A dedicated optimisation study was performed to design signal region (SR) selection criteria and to maximise the signal sensitivity. Four hard-lepton signal regions and two soft-lepton signal regions are defined, targeting different mass hierarchy scenarios in the simplified model. The selection criteria used to define the signal regions are summarised in

Table 2 for the soft-lepton channel and in Table 3 for the hard-lepton channel.

The observables defined below are used in the event selection.

The transverse mass (m_T) of the lepton and the $\boldsymbol{p}_T^{\text{miss}}$ is defined as

$$m_T = \sqrt{2 p_T^\ell E_T^{\text{miss}} (1 - \cos[\Delta\phi(\boldsymbol{p}_T^\ell, \boldsymbol{p}_T^{\text{miss}})])}, \tag{1}$$

where $\Delta\phi(\boldsymbol{p}_T^\ell, \boldsymbol{p}_T^{\text{miss}})$ is the azimuthal angle between the lepton and the missing transverse momentum. This is used in the soft-lepton 2-jet signal region and all hard-lepton signal regions to reject W+jets and semileptonic $t\bar{t}$ events.

The inclusive effective mass ($m_{\text{eff}}^{\text{inc}}$) is the scalar sum of the p_T of the signal lepton and jets and the E_T^{miss}:

$$m_{\text{eff}}^{\text{inc}} = p_T^\ell + \sum_{j=1}^{N_{\text{jet}}} p_{T,j} + E_T^{\text{miss}}, \tag{2}$$

where the index j runs over all the signal jets in the event with $p_T > 30$ GeV. The inclusive effective mass provides good discrimination against SM backgrounds, without being too sensitive to the details of the SUSY cascade decay chain.

The transverse momentum scalar sum (H_T) is defined as

$$H_T = p_T^\ell + \sum_{j=1}^{N_{\text{jet}}} p_{T,j}, \tag{3}$$

where the index j runs over all the signal jets in the event. The H_T variable is used to define the soft-lepton 5-jet signal region, as the many energetic jets in the signal model render this variable useful to separate signal from background.

The ratio $E_T^{\text{miss}}/m_{\text{eff}}^{\text{inc}}$ is used in both the soft- and the hard-lepton channels; it provides good discrimination power between signal and background with fake E_T^{miss} due to instrumental effects.

Additional suppression of background processes is based on the aplanarity variable, which is defined as $\mathcal{A} = \frac{3}{2}\lambda_3$, where λ_3 is the smallest eigenvalue of the normalised momentum tensor of the jets [76]. Typical measured values lie in the range $0 \leqslant \mathcal{A} < 0.3$, with values near zero indicating relatively planar background-like events.

The hard-lepton 5-jet region targets scenarios with high gluino masses and low $\tilde{\chi}_1^0$ masses in models with the chargino mass $m_{\tilde{\chi}_1^\pm}$ chosen such that the mass-ratio parameter $x = 1/2$. Tight requirements on m_T and $m_{\text{eff}}^{\text{inc}}$ are applied. For the same set of models, the hard-lepton 6-jet region is designed to provide sensitivity to scenarios where the mass separation between the gluino and the neutralino is smaller. For this reason, the requirements on m_T and $m_{\text{eff}}^{\text{inc}}$ are relaxed with respect to the hard-lepton 5-jet region. Two distinct hard-lepton 4-jet

Table 2 Overview of the selection criteria for the soft-lepton signal regions. The symbol p_T^ℓ refers to signal leptons

	2-jet soft-lepton SR	5-jet soft-lepton SR
$N_{\mathrm{lep}}(p_T^{\ell=e(\mu)} > 7(6)\ \mathrm{GeV})$	$=1$	$=1$
$p_T^{\ell=e(\mu)}$ (GeV)	7(6)–35	7(6)–35
N_{jet}	≥ 2	≥ 5
p_T^{jet} (GeV)	>180, 30	> 200, 200, 200, 30, 30
E_T^{miss} (GeV)	>530	>375
m_T (GeV)	>100	–
$E_T^{\mathrm{miss}}/m_{\mathrm{eff}}^{\mathrm{inc}}$	>0.38	–
H_T (GeV)	–	>1100
Jet aplanarity	–	>0.02

Table 3 Overview of the selection criteria for the hard-lepton signal regions. The symbol p_T^ℓ refers to signal leptons. The mass-ratio parameter x used in the signal region labels is defined in Sect. 3

	4-jet high-x SR	4-jet low-x SR	5-jet SR	6-jet SR
$N_{\mathrm{lep}}(p_T^{\ell=e(\mu)}>10\ \mathrm{GeV})$	$= 1$	$= 1$	$= 1$	$= 1$
$p_T^{\ell=e(\mu)}$ (GeV)	>35	>35	>35	>35
N_{jet}	≥ 4	≥ 4	≥ 5	≥ 6
p_T^{jet} (GeV)	>325, 30, ..., 30	>325, 150, ..., 150	>225, 50, ..., 50	>125, 30, ..., 30
E_T^{miss} (GeV)	>200	>200	>250	>250
m_T (GeV)	>425	>125	>275	>225
$E_T^{\mathrm{miss}}/m_{\mathrm{eff}}^{\mathrm{inc}}$	>0.3	–	>0.1	>0.2
$m_{\mathrm{eff}}^{\mathrm{inc}}$ (GeV)	>1800	>2000	>1800	>1000
Jet aplanarity	–	>0.04	>0.04	>0.04

regions are used, both designed to target models where the neutralino mass is fixed to 60 GeV, while the gluino mass and the mass-ratio x vary. The 4-jet high-x region is designed for regions of the parameter space where the W boson produced in the chargino decay is significantly boosted, leading to high-p_T leptons. The main characteristics of signal events in the phase-space of this model are large m_T values and relatively soft jets emitted from the gluino decays. In the 4-jet low-x region, the W boson tends to be virtual while the jets from the gluino decays tend to have high p_T due to the large gluino–chargino mass difference. Therefore, the m_T requirement is relaxed and more stringent jet p_T requirements are imposed.

The soft-lepton channels focus on models with compressed mass spectra. The soft-lepton 2-jet region provides sensitivity to scenarios characterised by a relatively heavy neutralino and a small mass separation between the gluino, the chargino and the neutralino. Due to the small mass separation, most of the decay products tend to be low p_T, or soft. Thus, a high-p_T initial-state radiation (ISR) jet recoiling against the rest of the event is required, in order to enhance the kinematic properties of the signal and to provide separation with respect to the backgrounds. The soft-lepton 5-jet region is designed to be sensitive to the configurations in

parameter space with a large mass gap between the gluino and chargino and a small separation between $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_1^0}$. As a consequence, several energetic jets from the decay of the two gluinos to the charginos are expected, while the virtual W bosons produced in the decay of the charginos result in low-p_T jets and leptons.

6 Background estimation

The two dominant background processes in final states with one isolated lepton, multiple jets and large missing transverse momentum are $t\bar{t}$ and W+jets. The differential distributions arising from these two background processes as predicted from simulation are simultaneously normalised to the number of data events observed in dedicated control regions (CR), through the fitting procedure explained in Sect. 8. The simulation is then used to extrapolate the measured background rates to the corresponding signal region.

The control regions are designed to have high purity in the process of interest, a small contamination from the signal model and enough events to result in a small statistical uncertainty in the background prediction. Moreover, they are designed to have kinematic properties resembling as closely

as possible those of the signal regions, in order to provide good estimates of the kinematics of background processes there. This procedure limits the impact of potentially large systematic uncertainties in the expected yields.

Additional sources of background events are single-top events (*s*-channel, *t*-channel and associated production with a *W* boson), *Z*+jets and diboson processes (*WW*, *WZ*, *ZZ*, *Wγ*, *Zγ*), and $t\bar{t}$ production in association with a *W* or a *Z* boson. Their contributions are estimated entirely using simulated event samples normalised to the most accurate theoretical cross-sections available.

The contribution from multi-jet processes with a misidentified lepton is found to be negligible once lepton isolation criteria and a stringent E_T^{miss} requirement are imposed. A data-driven matrix method, following the implementation described in Ref. [16], confirms this background is consistent with zero. This is mainly a result of the improved lepton reconstruction and identification and the higher threshold on E_T^{miss} with respect to the previous searches performed in this final state [16]. As this background is found to be negligible it is ignored in all aspects of the analysis.

Figure 2 visualises the criteria that define the control regions in the soft-lepton and hard-lepton channels. Based on these, separate control regions are defined to extract the normalisation factors for $t\bar{t}$ and *W*+jets by requiring at least one, or no, *b*-tagged signal jets, respectively. The cross-contamination between these two types of control regions is accounted for in the fit.

Figure 3 shows the E_T^{miss} distribution in selected soft-lepton and hard-lepton control regions. The normalisation of the *W*+jets and $t\bar{t}$ simulations are adjusted to match the observed number of data events in the control region, so that the plots illustrate the modelling of the shape of each variable's distribution. In general, good agreement between data and background simulations is found within the uncertainties in all the control regions used in the analysis.

To gain confidence in the extrapolation from control to signal regions using simulated event samples, the results of the simultaneous fit are cross-checked in validation regions which are disjoint with both the control and the signal regions. The validation regions are designed to be kinematically close to the signal regions, as shown in Fig. 2, while expecting only a small contamination from the signal in the models considered in this search. The validation regions are not used to constrain parameters in the fit, but they provide a statistically independent cross-check of the extrapolation.

This analysis uses two validation regions per signal region. In the hard-lepton channel, one of the validation regions is used to test the extrapolation to larger m_T values, while the other validation region tests the extrapolation to larger aplanarity values or, in the case of the 4-jet high-*x* selection, to larger values in $E_T^{miss}/m_{eff}^{incl}$. In the soft-lepton channel, the validation regions are used to test the extrapolation to larger E_T^{miss}, m_T or H_T values.

7 Systematic uncertainties

Two categories of systematic uncertainties have an impact on the results presented here: uncertainties arising from experimental effects and uncertainties associated with theoretical predictions and modelling. Their effects are evaluated for all signal samples and background processes. Since the normalisation of the dominant background processes is extracted in dedicated control regions, the systematic uncertainties only affect the extrapolation to the signal regions in these cases.

Among the dominant experimental systematic uncertainties are the jet energy scale (JES) and resolution (JER) and the muon momentum resolution. The jet uncertainties are derived as a function of p_T and η of the jet, as well as of the pile-up conditions and the jet flavour composition of the selected jet sample. They are determined using a combination of simulated samples and studies of data, such as measurements of the jet balance in dijet, *Z*+jet and *γ*+jet events [77]. The $J/\psi \to \ell^+\ell^-$, $W^{\pm} \to \ell^{\pm}\nu$ and $Z \to \ell^+\ell^-$ decays in data and simulation are exploited to estimate the uncertainties in lepton reconstruction, identification, momentum/energy scale and resolution and isolation criteria [69,70]. In particular, muon momentum resolution and scale calibrations are derived for simulation from a template fit that compares the invariant mass of $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ candidates in data and simulation. The corresponding uncertainties are computed from variations of several fit parameters, following the procedure described in Ref. [78].

The simulation is reweighted to match the distribution of the average number of proton-proton interactions per bunch crossing observed in data. In the signal regions characterised by a higher jet multiplicity, the uncertainty arising from this reweighting also becomes relevant.

The systematic uncertainties related to the modelling of E_T^{miss} in the simulation are estimated by propagating the uncertainties on the energy and momentum scale of each of the objects entering the calculation, as well as the uncertainties on the soft term resolution and scale.

Different uncertainties in the theoretical modelling of the SM production processes are considered, as described in the following.

For $t\bar{t}$, single-top and *W/Z*+jets samples, the uncertainties related to the choice of QCD renormalisation and factorisation scales are assessed by varying the corresponding generator parameters up and down by a factor of two around their nominal values. Uncertainties in the resummation scale and the matching scale between matrix elements and parton shower are evaluated for the *W*+jets samples by varying up
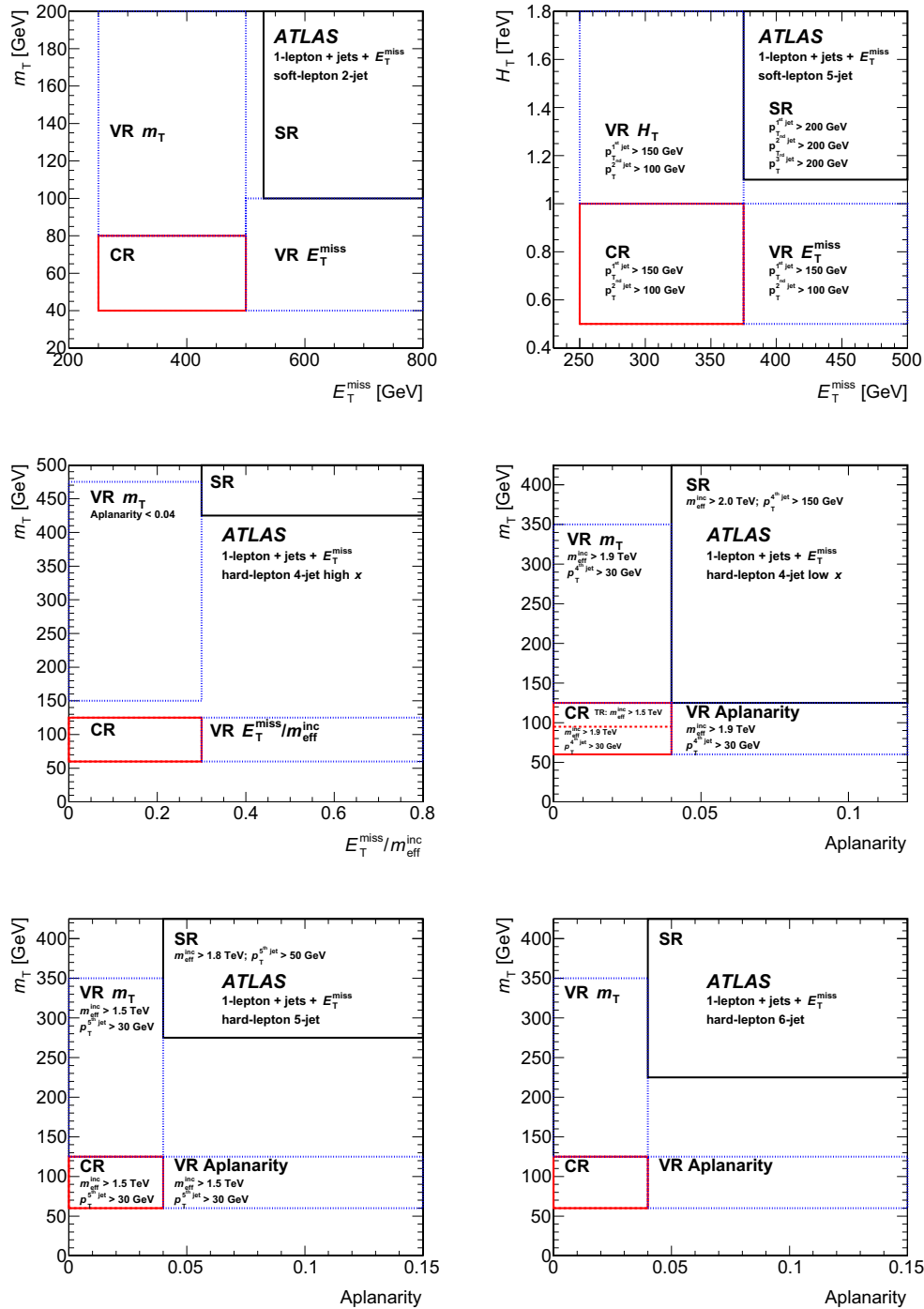
Fig. 2 Graphical illustration of the soft-lepton 2-jet (*top left*), soft-lepton 5-jet (*top right*), hard-lepton 4-jet high-*x* (*middle left*), 4-jet low-*x* (*middle right*), 5-jet (*bottom left*) and 6-jet (*bottom right*) signal (SR), control (CR) and validation (VR) regions. In addition to the two variables shown on the *x* and *y* axes, labels indicate other event selec- tions that differ between the corresponding control regions, validation regions and signal regions. The control regions exist in two variants: the $t\bar{t}$ control regions require at least one *b*-tagged jet, while no *b*-tagged jets are required in the *W*+jets control regions

and down by a factor of two the corresponding parameters in SHERPA .

For $t\bar{t}$ and single-top production, specific samples with an increased and decreased amount of initial- and final-state radiation are compared to the nominal sample. The relative difference in the extrapolation factors ($t\bar{t}$) or expected rates (single top) is assigned as an uncertainty. Moreover, the uncertainty associated with the parton-shower modelling
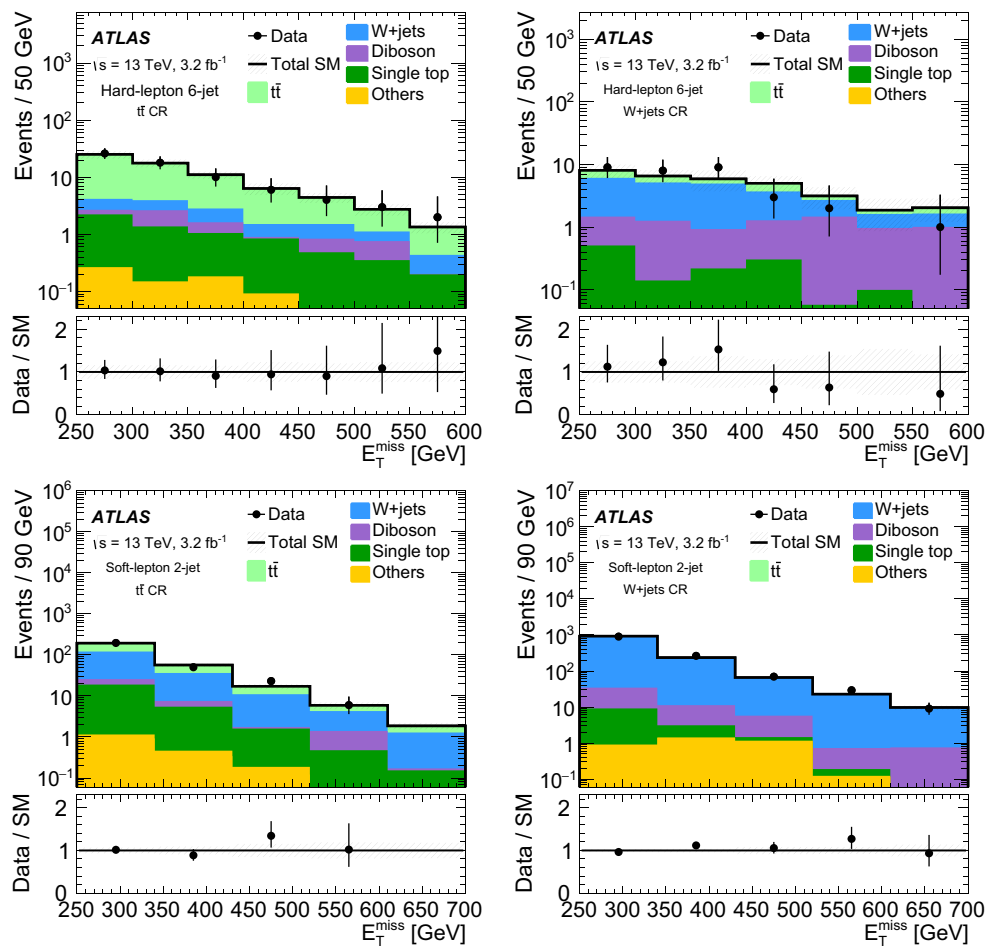
Fig. 3 The distribution of the missing transverse momentum is shown in hard-lepton 6-jet $t\bar{t}$ (*top left*) and W+jets (*top right*) and in the soft-lepton 2-jet $t\bar{t}$ (*bottom left*) and W+jets (*bottom right*) control regions after normalising the $t\bar{t}$ and W+jets background processes in the simultaneous fit. In the soft-lepton 2-jet plots, the upper bound on E_T^{miss} defining the control region is not applied. The *lower panels* of the plots show the ratio of the observed data to the total SM background expected from simulations scaled to the number of events observed in the data. The uncertainty bands include all statistical and systematic uncertainties on simulation, as discussed in Sect. 7. The component 'Others' is the sum of Z+jets and $t\bar{t}$+V

is assessed as the difference between the predictions from POWHEG+PYTHIA and POWHEG+HERWIG++[2] [79].

An uncertainty arising from the choice of parton level generator is estimated for $t\bar{t}$, diboson and W/Z+jets processes. In the former case, the predictions from POWHEG-BOX are compared to AMC@NLO[3] [80]; for dibosons, SHERPA is compared to POWHEG-BOX; for W/Z+jets, SHERPA is compared to MADGRAPH [81].

An uncertainty of 5 % in the inclusive Z+jets cross-section is assumed [82]. Uncertainties in the inclusive single-top cross-sections are assigned as 3.7 % (*s*-channel, top), 4.7 % (*s*-channel, anti-top), 4 % (*t*-channel, top), 5 % (*t*-channel, anti-top) and 5.3 % (*Wt*-channel) [83]. Samples using dia-

gram subtraction and diagram removal schemes are compared for assessing the sensitivity to the treatment of interference effects between single-top and $t\bar{t}$ production at NLO.

An overall systematic uncertainty of 6 % in the inclusive cross-section is assigned to the small contribution from WW, WZ, ZZ, $W\gamma$ and $Z\gamma$ processes, which are estimated entirely from simulation. The uncertainty accounts for missing higher-order corrections, for the uncertainty in the value of the strong coupling constant and for the uncertainties on the PDF sets. The uncertainties associated with the resummation, factorisation and renormalisation scales are computed by varying the corresponding SHERPA parameters.

For the very small contributions of $t\bar{t} + W/Z/WW$, an uncertainty of 30 % is assigned.

Among the main systematic uncertainties on the total background predictions in the various signal regions are the

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[2] The HERWIG++ version 2.7.1 used.

[3] The AMC@NLO version 2.1.1 is used.

ones associated with the finite size of the MC samples, which range from 11 % in the hard-lepton 6-jet SR to 33 % in the hard-lepton 4-jet high-*x* SR. Moreover, the uncertainties associated with the normalisation of the $t\bar{t}$ background, ranging from 7 % in the soft-lepton 5-jet SR to 21 % in the hard-lepton 4-jet low-*x* SR. Further important uncertainties are the theoretical uncertainties associated with the single-top background in the hard-lepton regions, which amount to

3 % in the 4-jet high-*x* signal region and increase to as much as 34 % in the 4-jet low-*x* signal region, and the theoretical uncertainties on the *W*+jets background in the soft-lepton regions (up to 11 %).

The theoretical systematic uncertainty affecting the modelling of ISR can become sizeable in the simplified signal models used in this analysis, especially when the SUSY particles' mass splitting becomes small. Variations of a factor of
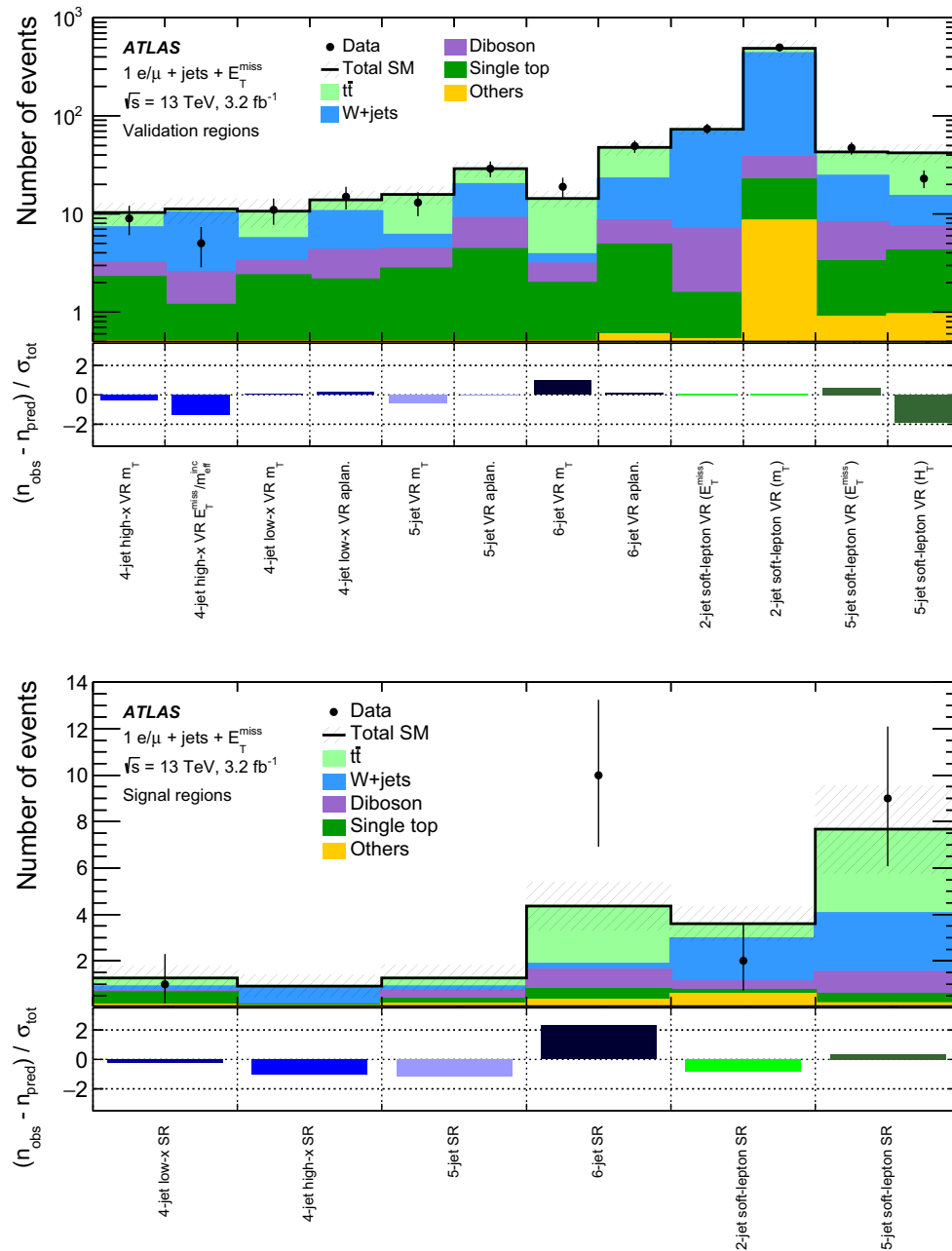
Fig. 4 Expected background yields as obtained in the background-only fits in all hard-lepton and soft-lepton validation (*top plot*) and signal (*bottom plot*) regions together with observed data are given in the *top parts* of the plots. Uncertainties in the fitted background estimates combine statistical (in the simulated event yields) and systematic uncertainties. The *bottom parts* of the plots show the differences between observed (n_{obs}) and predicted n_{pred} event yields, divided by the total (statistical and systematic) uncertainty in the prediction (σ_{tot}). *Bars sharing the same colour* belong to regions fitted in the same background-only fit

Table 4 Background fit results for the hard-lepton and soft-lepton signal regions, for an integrated luminosity of 3.2 fb^{-1}. Uncertainties in the fitted background estimates combine statistical (in the simulated event yields) and systematic uncertainties. The uncertainties in this table are symmetrised for propagation purposes but truncated at zero to remain within the physical boundaries

	Hard-lepton				Soft-lepton	
	4-jet low x	4-jet high x	5-jet	6-jet	2-jet	5-jet
Observed events	1	0	0	10	2	9
Fitted background events	1.3 ± 0.5	0.9 ± 0.5	1.3 ± 0.6	4.4 ± 1.0	3.6 ± 0.7	7.7 ± 1.9
$t\bar{t}$	0.40 ± 0.31	0.08 ± 0.07	0.40 ± 0.24	2.5 ± 0.9	0.64 ± 0.33	3.6 ± 1.2
W+jets	0.19 ± 0.12	0.8 ± 0.5	0.16 ± 0.12	0.23 ± 0.16	1.9 ± 0.5	2.5 ± 1.3
Z+jets	0.045 ± 0.023	0.028 ± 0.027	0.073 ± 0.035	0.08 ± 0.08	0.47 ± 0.12	0.09 ± 0.04
Single top	0.5 ± 0.5	$0.04^{+0.10}_{-0.04}$	$0.21^{+0.22}_{-0.21}$	0.4 ± 0.4	0.16 ± 0.14	0.42 ± 0.33
Diboson	$0.06^{+0.20}_{-0.06}$	$0.002^{+0.014}_{-0.002}$	0.37 ± 0.23	0.9 ± 0.5	0.38 ± 0.16	0.9 ± 0.6
$t\bar{t}$+V	0.048 ± 0.021	0.024 ± 0.012	0.059 ± 0.029	0.23 ± 0.08	0.085 ± 0.028	0.065 ± 0.024

two in the following MADGRAPH and PYTHIA parameters are used to estimate these uncertainties: the renormalisation and factorisation scales, the initial- and the final-state radiation scales, as well as the MADGRAPH jet matching scale. The overall uncertainties range from about 5 % for signal models with large mass differences between the gluino, the chargino and the neutralino, to 25 % for models with very compressed mass spectra.

8 Statistical analysis

The final results are based on a profile likelihood method [84] using the HistFitter framework [85]. To obtain a set of background predictions that is independent of the observation in the signal regions, the fit can be configured to use only the control regions to constrain the fit parameters; this is referred to as the background-only fit. For each signal region a background-only fit is performed, based on the following inputs:

- the observed number of events in each of the control regions associated with the signal region, together with the number of events expected from simulation;
- the extrapolation factors, including uncertainties, from control regions to the signal region, as obtained from simulation, for the W+jets and the $t\bar{t}$ backgrounds;
- the yields of the smaller backgrounds such as the single top, $t\bar{t}$+V, Z+jets and diboson backgrounds as obtained from simulation, including uncertainties.

Using this information a likelihood is constructed for every background-only fit. It consists of a product of Poisson probability density functions for every region and of constraint terms for systematic uncertainties as described below.

Multiple parameters are included in each likelihood: two normalisation parameters describing the normalisation of the W+jets and $t\bar{t}$ backgrounds and nuisance parameters associated with the systematic uncertainties (as described in Sect. 7) or the statistical uncertainties in simulated event yields. The nuisance parameters associated with the systematic uncertainties are constrained by Gaussian functions with their widths corresponding to the size of the uncertainty, while the statistical uncertainties are constrained by Poisson functions. The parameters are correlated between the control regions and the signal region.

In the fit, the likelihood is maximised by adjusting normalisation and nuisance parameters. The normalisation scale factor of the $t\bar{t}$ background is fitted to values between $0.34^{+0.28}_{-0.25}$ (4-jet high-x control regions) and $0.92^{+0.14}_{-0.12}$ (5-jet soft-lepton control regions), the normalisation of the W+jets background to values between $0.72^{+0.31}_{-0.33}$ (6-jet control regions) and 1.00 ± 0.04 (2-jet soft-lepton control regions). Previous analyses [16] also found normalisation factors considerably smaller than unity for these background processes in similarly extreme regions of phase space. The fit introduces correlations between the normalisation parameters associated with the $t\bar{t}$ and the W+jets backgrounds and the nuisance parameters associated with systematic uncertainties. The uncertainty in the total background estimate may thus be smaller or larger than the sum in quadrature of the individual uncertainties.

9 Results

The results of the background-only fit described in Sect. 8 in the validation and signal regions are shown in Fig. 4 and are further detailed for the signal regions in Table 4. Good agreement between predicted and observed event yields is seen in all validation regions.

Figure 5 shows the m_{T}, $E_{\text{T}}^{\text{miss}}$ and $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}^{\text{incl}}$ distributions before applying the requirement on the plotted variable in the signal regions.
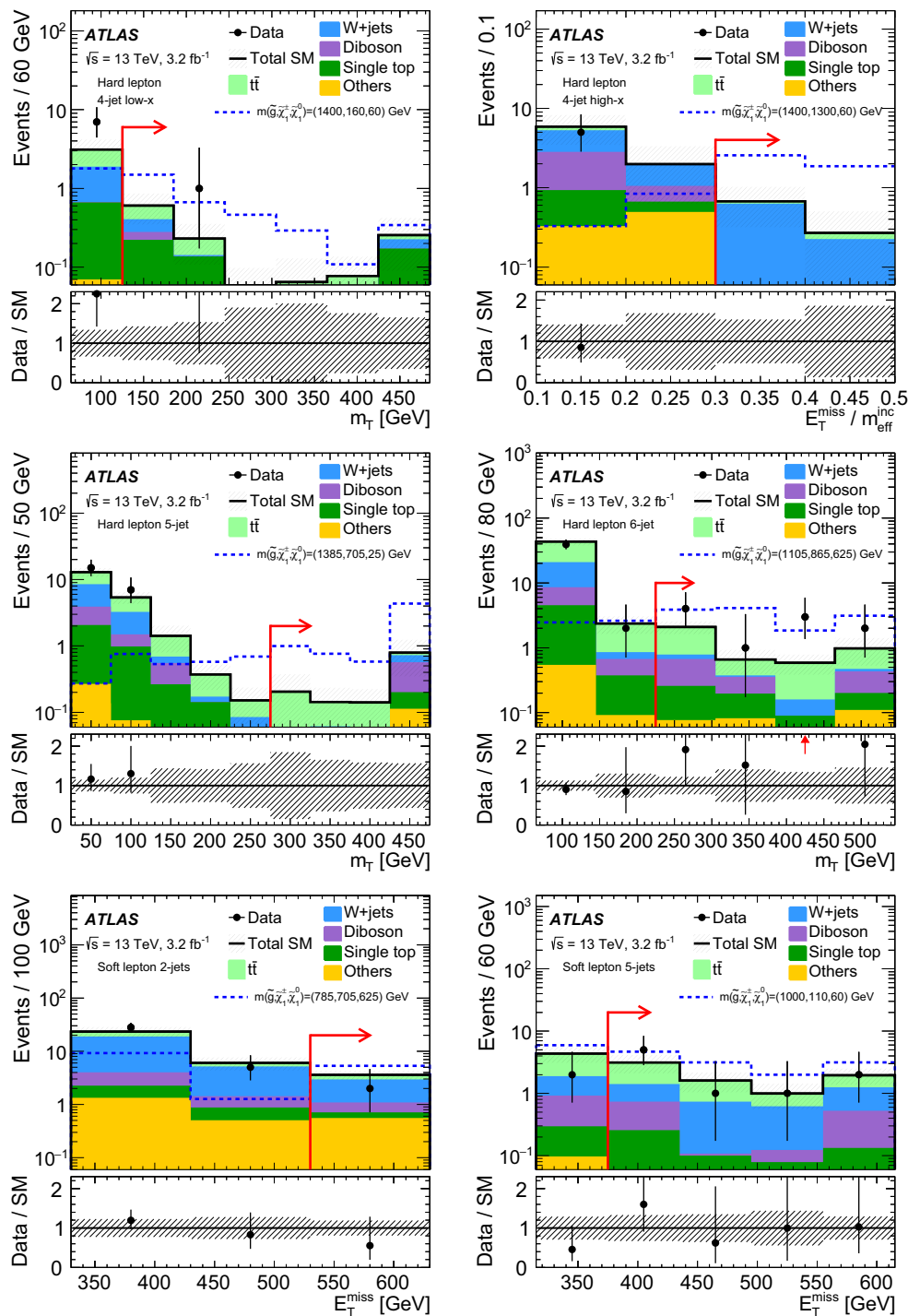
Fig. 5 Distributions of m_T for the hard-lepton 4-jet low-x (*top left*), 5-jet (*middle left*), 6-jet (*middle right*) signal regions, of $E_T^{miss}/m_{eff}^{incl}$ for the 4-jet high-x signal region (*top right*) and of E_T^{miss} for the soft-lepton 2-jet (*bottom left*) and soft-lepton 5-jet (*bottom right*) signal regions. The requirement on the variable plotted is removed from the definitions of the signal regions, where the *arrow* indicates the position of the cut

in the signal region. The *lower panels* of the plots show the ratio of the observed data to the total background prediction as derived in the background-only fit. The uncertainty bands plotted include all statistical and systematic uncertainties as discussed in Sect. 7. The component 'Others' is the sum of Z+jets and $t\bar{t}$+V. The last bin includes the overflow

The predicted background yields and the observed number of events agree in all signal regions. The largest deviation, 2.1 standard deviations, is observed in the 6-jet hard-lepton

signal region. This excess arises only from the muon channel, in which 8 events are observed, while 2.5 ± 0.7 events are predicted (local significance of 2.6 standard deviations).

Table 5 The columns show from left to right: the name of the respective signal region; the 95 % confidence level (CL) upper limits on the visible cross-section ($\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$) and on the number of signal events (S^{95}_{obs}); the 95 % CL upper limit on the number of signal events (S^{95}_{exp}), given the expected number (and $\pm1\sigma$ variations on the expectation) of background events; the two-sided CL_b value, i.e. the confidence level observed for the background-only hypothesis and the one-sided discovery p-value ($p(s=0)$). The discovery p values are capped to 0.5 in the case of observing less events than the fitted background estimates

Signal region	$\langle\epsilon\sigma\rangle^{95}_{\mathrm{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	$p(s=0)$
Hard-lepton					
4-jet low-x	1.23	3.9	$4.1^{+1.5}_{-0.9}$	0.46	0.50
4-jet high-x	0.87	2.8	$2.9^{+1.3}_{-0.2}$	0.27	0.50
5-jet	0.87	2.8	$3.5^{+1.4}_{-0.7}$	0.19	0.50
6-jet	3.90	12.5	$6.5^{+2.6}_{-1.6}$	0.98	0.02
Soft-lepton					
2-jet	1.33	4.3	$5.3^{+2.2}_{-1.3}$	0.23	0.50
5-jet	2.87	9.2	$8.1^{+2.9}_{-2.1}$	0.68	0.34

The electron channel shows good agreement, with 2 events observed and 1.9 ± 0.6 predicted.

Model-independent upper limits and discovery p values [85] in the signal regions are calculated in a modified fit configuration with respect to the background-only fit. The only region considered in these fits is the respective signal region. Control regions are not explicitly included and thus any signal contamination in the control regions is not taken into account, thus giving conservative limits. These fits use the background estimates as derived in the background-only fits as input and allow for a non-negative signal contribution in the signal region. An additional normalisation parameter for the signal contribution is included.

Observed and expected upper limits at 95 % confidence level (CL) on the number of events signifying new phenomena beyond the SM (S^{95}_{obs} and S^{95}_{exp}, respectively) are derived based on the CL_s prescription [86] and are shown in Table 5 together with the upper limits on the visible beyond the SM cross-section (σ_{vis}, defined as the product of acceptance, selection efficiency and production cross-section). The latter is calculated by dividing the observed upper limit on the beyond-SM events by the integrated luminosity of 3.2 fb^{-1}. The table also gives the background-only confidence level CL_b.

Table 5 also shows the discovery p values, giving the probability for the background-only assumption to produce event yields greater or equal to the observed data. The CL_b and p values use different definitions of test statistics in their calculation, the former with the signal-strength parameter set to one and the latter to zero.

Model-dependent limits are calculated in a modified fit configuration with respect to the background-only fit. A sig-
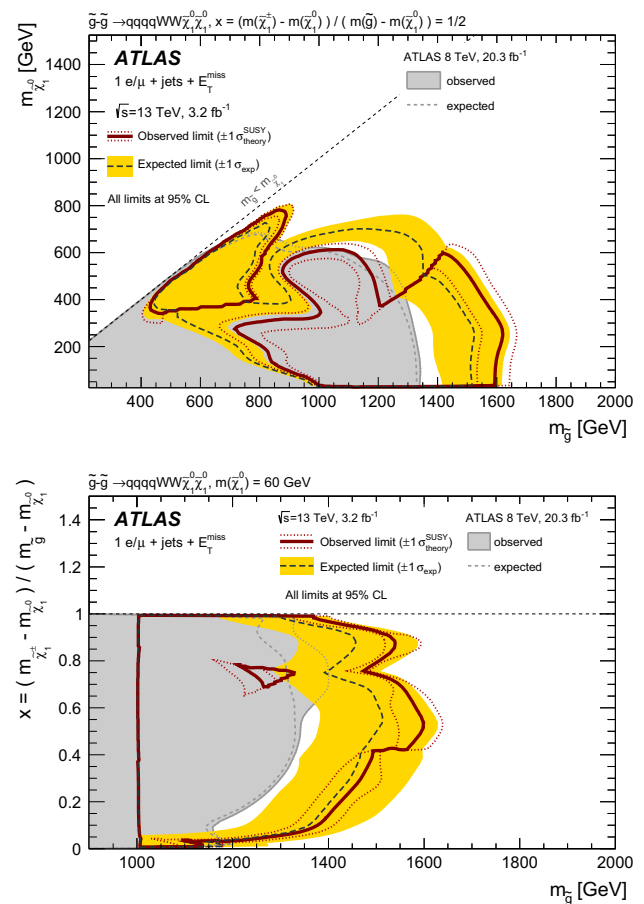
Fig. 6 Combined 95 % CL exclusion limits in the two gluino simplified models using for each model point the signal region with the best expected sensitivity. The limits are presented in the $(m_{\tilde{g}}, m_{\tilde{\chi}^0_1})$ mass plane (*top*) for the scenario where the mass of the chargino $\tilde{\chi}^{\pm}_1$ is fixed to $x = (m_{\tilde{\chi}^{\pm}_1} - m_{\tilde{\chi}^0_1})/(m_{\tilde{g}} - m_{\tilde{\chi}^0_1}) = 1/2$ and in the $(m_{\tilde{g}}, x)$ plane (*bottom*) for the $m_{\tilde{\chi}^0_1} = 60$ GeV models. The *red solid line* corresponds to the observed limit with the *red dotted lines* indicating the $\pm1\sigma$ variation of this limit due to the effect of theoretical scale and PDF uncertainties in the signal cross-section. The *dark grey dashed line* indicates the expected limit with the *yellow band* representing the $\pm1\sigma$ variation of the median expected limit due to the experimental and theoretical uncertainties. The exclusion limits at 95 % CL by previous ATLAS analyses [17] are shown as the *grey area*

nal contribution is allowed and considered in all control and signal regions, with a non-negative signal-strength normalisation parameter included. For the signal processes, uncertainties due to detector effects and theoretical modelling are considered. The signal regions are explicitly used in the fit to constrain the likelihood parameters. Figure 6 shows the combined 95 % CL exclusion limits in the simplified models with gluino production using for each model point the signal region with the best expected sensitivity. Gluino masses up to 1.6 TeV are excluded for scenarios with large mass differences between the gluino and the neutralino and $x = (m_{\tilde{\chi}^{\pm}_1} - m_{\tilde{\chi}^0_1})/(m_{\tilde{g}} - m_{\tilde{\chi}^0_1}) = 1/2$. In the same scenario

and for models with a small mass difference between the gluino and the neutralino, gluino masses up to 870 GeV are excluded. The signal regions address very different sets of models and are complementary to each other. In the case of the hard-lepton 6-jet signal region (covering the central part in the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ mass plane in Fig. 6), the observed exclusion limit is considerably weaker than the expected one due to the excess seen in this region.

10 Conclusion

A search for gluinos in events with one isolated lepton, jets and missing transverse momentum is presented. The analysis uses 3.2 fb^{-1} of proton–proton collision data collected by the ATLAS experiment in 2015 at $\sqrt{s} = 13$ TeV at the LHC. Six signal regions requiring at least two to six jets are used to cover a broad spectrum of the targeted SUSY model parameter space. While four signal regions are based on high-p_T lepton selections and target models with large mass differences between the supersymmetric particles, two dedicated low-p_T lepton regions are designed to enhance the sensitivity to models with compressed mass spectra.

The observed data agree with the Standard Model background prediction in the signal regions. The largest deviation is a 2.1 standard deviation excess in a channel requiring a high-p_T lepton and six jets. For all signal regions, limits on the visible cross-section are derived in models of new physics within the kinematic requirements of this search. In addition, exclusion limits are placed on models with gluino production and subsequent decays via an intermediate chargino to the lightest neutralino. The exclusion limits of previous searches conducted in LHC Run 1 are significantly extended. Gluino masses up to 1.6 TeV are excluded for low neutralino masses ($\lesssim 300$ GeV) and chargino masses of ~ 850 GeV.

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