Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Search for Supersymmetry in Events with Large Missing Transverse Momentum, Jets, and at Least One Tau Lepton in 7 TeV Proton-Proton Collision Data with the ATLAS Detector

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Received: date / Accepted: date

Abstract A search for supersymmetry (SUSY) in events with large missing transverse momentum, jets, and at least one hadronically decaying τ lepton, with zero or one additional light lepton (e/μ), has been performed using $4.7\,\mathrm{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 7\,\mathrm{TeV}$ recorded with the ATLAS detector at the Large Hadron Collider. No excess above the Standard Model background expectation is observed and a 95 % confidence level visible cross-section upper limit for new phenomena is set. In the framework of gauge-mediated SUSY-breaking models, lower limits on the mass scale Λ are set at 54 TeV in the regions where the $\tilde{\tau}_1$ is the next-to-lightest SUSY particle ($\tan\beta > 20$). These limits provide the most stringent tests to date of GMSB models in a large part of the parameter space considered.

Keywords ATLAS · SUSY · taus · GMSB

1 Introduction

This paper reports on the search for supersymmetry (SUSY) [1–9] in events with large missing transverse momentum, jets and at least one hadronically decaying τ lepton. Four different topologies with a τ in the final state have been studied: one τ lepton, at least two τ leptons, one τ lepton and precisely one additional muon and one τ lepton and precisely one additional electron. The minimal gauge-mediated supersymmetry-breaking (GMSB) model [10–15] is considered as benchmark to evaluate the reach of this analysis.

SUSY introduces a symmetry between fermions and bosons, resulting in a SUSY partner (sparticle) for each Standard Model (SM) particle with identical mass and quantum numbers except a difference by half a unit of spin. Assuming R-parity conservation [16–20], sparticles are produced in pairs. These would then decay through cascades involving other sparticles until the lightest SUSY particle (LSP), which is stable, is produced. Since equal mass SUSY partners are excluded, SUSY must be a broken symmetry. Minimal GMSB models can be described by six parameters: the SUSY-breaking mass scale in the low-energy sector (Λ), the messenger mass (M_{mess}), the number of SU(5) messenger fields (N_5), the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$), the Higgs-sector mixing parameter (μ) and the scale factor for the gravitino mass (C_{grav}). For the analysis presented in this paper, Λ and $\tan\beta$ are treated as free parameters, and the other parameters are fixed to the values already used in Refs. [21, 22]: $M_{\mathrm{mess}} = 250\,\mathrm{TeV}$, $N_5 = 3$, $\mu > 0$ and $C_{\mathrm{grav}} = 1$. The C_{grav} parameter determines the lifetime of next-to-lightest SUSY particle (NLSP); for $C_{\mathrm{grav}} = 1$ the NLSP decays promptly ($c\tau_{\mathrm{NLSP}} < 0.1\,\mathrm{mm}$). With this choice of parameters, at moderate Λ the production of gluino and/or squark pairs is expected to dominate at the LHC; these sparticles will decay into the next-to-lightest SUSY particle (NLSP), which subsequently decays to the LSP. In GMSB models, the LSP is the very light gravitino ($\tilde{G}$). The NLSP is the dominant sparticle decaying to the LSP and this leads to experimental signatures which are largely determined by the nature of the NLSP. This can be either the lightest stau ($\tilde{\tau}_1$), a right-handed slepton ($\tilde{\ell}_R$), the lightest neutralino ($\tilde{\chi}_1^0$), or a sneutrino ($\tilde{\nu}$), dominantly leading to final states containing τ leptons, light leptons ($\ell = e, \mu$), photons, b-jets, or neutrinos. At large values of $\tan\beta$, the $\tilde{\tau}_1$ is the NLSP for most of the parameter space, which leads to final states containing at least two τ leptons. In the so-called CoNLSP region, where the mass difference between the $\tilde{\tau}_1$ and the $\tilde{\ell}_R$ is smaller than the sum of the

τ and light-lepton masses, both the $\tilde{\tau}_1$ and the $\tilde{\ell}_R$ decay directly into the LSP and are therefore NLSPs.

Previous searches for $\tilde{\tau}_1$ pair production, with the subsequent decay $\tilde{\tau}_1 \to \tau\tilde{G}$ in the minimal GMSB model, have been reported by the LEP Collaborations ALEPH [23], DELPHI [24] and OPAL [25]. The analysis reported in this paper extends the searches in $2\,\mathrm{fb}^{-1}$ of data presented in Refs. [21, 22]. It comprises the full 2011 dataset, corresponding to an integrated luminosity of $(4.7 \pm 0.1)\,\mathrm{fb}^{-1}$ [26, 27] after applying beam, detector and data-quality requirements. A complementary search interpreted in GMSB, requiring two light leptons, has also been performed using the same dataset by the ATLAS collaboration [28]. The CMS Collaboration has searched for new phenomena in same-sign τ-pair events [29] and multi-lepton events including two τ leptons in the final state [30] using $35\,\mathrm{pb}^{-1}$ of data, where the minimal GMSB model was not considered.

2 ATLAS detector

The ATLAS experiment [31] is a multi-purpose detector with a forward-backward symmetric cylindrical geometry and nearly 4π solid angle coverage. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field and by fine-granularity lead/liquid-argon (LAr) electromagnetic calorimeters. An iron/scintillator-tile calorimeter provides hadronic coverage in the central pseudorapidity[1] range. The endcap and forward regions are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. An extensive muon spectrometer system that incorporates large superconducting toroidal magnets surrounds the calorimeters.

3 Simulated samples

The Monte Carlo (MC) simulations used to evaluate the expected backgrounds and selection efficiencies for the SUSY models considered are very similar to the ones used in Refs. [21, 22]. A suite of generators is used to aid in the estimate of SM background contributions. The `ALPGEN` generator [32] is used to simulate samples of W and Z/γ^* events with up to five (for Z events) or six (for W events) accompanying jets, where `CTEQ6L1` [33] is used for the parton distribution functions (PDFs). Z/γ^* events with $m_{\ell\ell} < 40$ GeV are referred to in this paper as “Drell-Yan”. Top quark pair production, single top production and diboson (WW and WZ) pair production are simulated with `MC@NLO` [34–36] and the next-to-leading-order (NLO) PDF set `CT10` [37]. Fragmentation and hadronization are performed with `Herwig` [38], using `JIMMY` [39] for the underlying event simulation. The decay of τ leptons and radiation of photons are simulated using `TAUOLA` [40, 41] and `PHOTOS` [42], respectively. The production of multijet events is simulated with `PYTHIA` 6.4.25 [43] using the AUET2B tune [44] and `MRST2007 LO*` [45] PDFs. The SUSY mass spectra are calculated using `ISAJET` 7.80 [46]. The MC signal samples are produced using `Herwig++` 2.4.2 [47] with `MRST2007 LO*` PDFs. Signal cross-sections are calculated to next-to-leading order in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [48–52]. The nominal SUSY production cross-sections and their uncertainties are taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalization scales, as described in Ref. [53]. The GMSB signal samples are generated on a grid ranging from $\Lambda = 10\,\mathrm{TeV}$ to $\Lambda = 80\,\mathrm{TeV}$ and from $\tan\beta = 2$ to $\tan\beta = 67$, with the cross-section dropping from 100 pb for $\Lambda = 15\,\mathrm{TeV}$ to 5.0 fb for $\Lambda = 80\,\mathrm{TeV}$.

All samples are processed through the GEANT4-based simulation [54] of the ATLAS detector [55]. The full simulation also includes a realistic treatment of the variation of the number of pp interactions per bunch crossing (pile-up) in the data, with an average of nine interactions per crossing.

4 Object reconstruction

Jets are reconstructed using the anti-k_t jet clustering algorithm [56] with radius parameter $R = 0.4$. Jet energies are calibrated to correct for upstream material, calorimeter non-compensation, pile-up, and other effects [57]. Jets are required to have transverse momenta (p_{T}) greater than 25 GeV and $|\eta| < 2.8$, except in the computation of the missing transverse momentum, where $|\eta| < 4.5$ and p_{T} greater than 20 GeV is required.

Muon candidates are identified as tracks in the ID matched to track segments in the muon spectrometer [58]. They are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.4$. Electron candidates are constructed by matching

[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 beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

Table 1 Event selection for the four final states presented in this paper. Numbers in parentheses are the minimum transverse momenta required for the objects. Pairs of numbers separated by a slash denote different selection criteria imposed in different data-taking periods.

–	1τ	2τ	τ+μ	τ+e
Trigger	jetMET $p_{\mathrm{T}}^{\mathrm{jet}} > 75\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} > 45/55\,\mathrm{GeV}$	jetMET $p_{\mathrm{T}}^{\mathrm{jet}} > 75\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} > 45/55\,\mathrm{GeV}$	muon/muon+jet $p_{\mathrm{T}}^{\mu} > 18\,\mathrm{GeV}$ $p_{\mathrm{T}}^{\mathrm{jet}} > 10\,\mathrm{GeV}$	electron $p_{\mathrm{T}}^{e} > 20/22\,\mathrm{GeV}$
Jet req. $E_{\mathrm{T}}^{\mathrm{miss}}$ req. $N_{e,\mu}$ N_{τ}	≥2 jets (130, 30 GeV) $E_{\mathrm{T}}^{\mathrm{miss}} > 130/150$ GeV 0 =1 medium (20 GeV), =0 loose	≥2 jets (130, 30 GeV) $E_{\mathrm{T}}^{\mathrm{miss}} > 130/150$ GeV 0 ≥2 loose (20 GeV)	≥1 jet (50 GeV) — 1 μ (20 GeV) ≥1 medium (20 GeV)	— — 1 e (25 GeV) ≥1 medium (20 GeV)
Kinematic criteria	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.3$; $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.3$, $m_{\mathrm{T}} > 110$ GeV; $H_{\mathrm{T}} > 775\,\mathrm{GeV}$	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.3$ $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} > 100\,\mathrm{GeV}$ $H_{\mathrm{T}} > 650\,\mathrm{GeV}$	$m_{\mathrm{T}}^{e,\mu} > 100$ GeV $m_{\mathrm{eff}} > 1000$ GeV	$m_{\mathrm{T}}^{e,\mu} > 100$ GeV $m_{\mathrm{eff}} > 1000$ GeV

electromagnetic clusters with tracks in the ID. They are then required to satisfy $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.47$ and to pass the "tight" identification criteria described in Ref. [59], re-optimized for 2011 conditions.

Electrons or muons are required to be isolated, i.e. the scalar sum of the transverse momenta of tracks within a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.2$ around the lepton candidate, excluding the lepton candidate track itself, must be less than 10% of the lepton's transverse energy for electrons and less than 1.8 GeV for muons. Tracks selected for the electron and muon isolation requirement defined above have $p_{\mathrm{T}} > 1$ GeV and are associated to the primary vertex of the event.

The missing transverse momentum vector $\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$ (and its magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) is measured from the transverse momenta of identified jets, electrons, muons and all calorimeter clusters with $|\eta| < 4.5$ not associated to such objects [60]. For the purpose of the measurement of $E_{\mathrm{T}}^{\mathrm{miss}}$, τ leptons are not distinguished from jets.

Jets originating from decays of b-quarks are identified and used to separate the W and $t\bar{t}$ background contributions. They are identified by a neural-network-based algorithm, which combines information from the track impact parameters with a search for decay vertices along the jet axis [61]. A working point corresponding to 60 % tagging efficiency for b-jets and < 1 % mis-identification of light-flavour or gluon jets is chosen [62].

The τ leptons considered in this search are reconstructed through their hadronic decays. The τ reconstruction is seeded from anti-k_t jets ($R = 0.4$) with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. An η- and p_{T}-dependent energy calibration to the hadronic τ energy scale is applied. Discriminating variables based on track information and observables sensitive to the transverse and longitudinal shape of the energy deposits of τ candidates in the calorimeter are used. These quantities are combined in a boosted decision tree (BDT) discriminator [63] to optimize their impact. Calorimeter information and measurements of transition radiation are used to veto electrons mis-identified as τ leptons. Suitable τ lepton candidates must satisfy $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $|\eta| < 2.5$, and have one or three associated tracks of $p_{\mathrm{T}} > 1\,\mathrm{GeV}$ with a charge sum of ±1. A sample of $Z \to \tau\tau$ events is used to measure the efficiency of the BDT τ identification. The "loose" and "medium" working points in Ref. [63] are used herein and correspond to efficiencies of about 60 % and 40 % respectively, independent of p_{T}, with a rejection factor of 20–50 against τ candidates built from hadronic jets ("fake" τ leptons).

5 Event Selection

Four mutually exclusive final states are considered for this search: events with only one "medium" τ, no additional "loose" τ candidates and no muons or electrons, referred to as '1τ'; events with two or more "loose" τ candidates and no muons or electrons, referred to as '2τ'; events with at least one "medium" τ and exactly one muon ('τ+μ') or electron ('τ+e').

In the 1τ and 2τ final states, candidate events are triggered by requiring a jet with high transverse momentum and high $E_{\mathrm{T}}^{\mathrm{miss}}$ ('jetMET') [65], both measured at the electromagnetic scale[2]. In the τ+μ final state,

[2]The electromagnetic scale is the basic calorimeter signal scale for the ATLAS calorimeters. It has been established using test-beam measurements for electrons and muons to

Table 2 Definition of the background control regions (CRs) used to estimate the normalization of background samples in the four final states: 1τ, 2τ, $\tau+\mu$ and $\tau+e$.

Background	1τ	2τ	$\tau+\mu$	$\tau+e$
$t\bar{t}$	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.3$ rad $m_{\mathrm{T}} < 70$ GeV $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.3$ b-tag template fit	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.3$ rad $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} \geq 100$ GeV $H_{\mathrm{T}} < 550$ GeV $N_{b-\mathrm{tag}} \geq 1$	30 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} <$ 100 GeV 50 GeV $< m_{\mathrm{T}}^{e,\mu} <$ 150 GeV $N_{b-\mathrm{tag}} \geq 1$	
W+jets	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.3$ rad $m_{\mathrm{T}} < 70$ GeV $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} > 0.3$	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.3$ rad $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} \geq 100$ GeV $H_{\mathrm{T}} < 550$ GeV $N_{b-\mathrm{tag}} = 0$	30 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} <$ 100 GeV 50 GeV $< m_{\mathrm{T}}^{e,\mu} <$ 150 GeV $N_{b-\mathrm{tag}} = 0$	
Z+jets	2μ (20 GeV), $\lvert\eta\rvert < 2.4$ $\geq$2 jets (130, 30 GeV) $N_{b-\mathrm{tag}} = 0$	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.3$ rad $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} < 80$ GeV $H_{\mathrm{T}} < 550$ GeV	MC-based normalization	
Multi-jet	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) < 0.3$ rad $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} < 0.3$	$\Delta(\phi_{\mathrm{jet}_{1,2}} - \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) < 0.3$ rad $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} < 0.4$	compare events with and without lepton isolation [64]	

events are selected by a muon trigger and a muon-plus-jet trigger ('muon+jet'), while in the $\tau+e$ final state, a single-electron trigger requirement is imposed [65]. The trigger requirements have been optimized to ensure a uniform trigger efficiency for all data-taking periods, which exceeds 98 % with respect to the offline selection for all final states considered.

Pre-selected events are required to have a reconstructed primary vertex with at least five tracks (with $p_{\mathrm{T}} > 0.4$ GeV). To suppress soft multi-jet events in the 1τ and 2τ final states, a second jet with $p_{\mathrm{T}} > 30$ GeV is required. Remaining multi-jet events, where highly energetic jets are mis-measured, are suppressed by requiring the azimuthal angle between the missing transverse momentum vector and either of the two leading jets to be greater than 0.3 rad. Three quantities characterising the kinematic properties of the event are used to further suppress the main background processes (W+jets, Z+jets and $t\bar{t}$ events) in all four final states:

- the transverse mass $m_{\mathrm{T}}^{\tau,\ell}$ formed by $E_{\mathrm{T}}^{\mathrm{miss}}$ and either the p_{T} of the τ lepton in the 1τ and 2τ channels, or of the light lepton (e/μ) in the $\tau+\mu$ and $\tau+e$ ones: $m_{\mathrm{T}}^{\tau,\ell} = \sqrt{2p_{\mathrm{T}}^{\tau,\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos(\Delta\phi(\tau/\ell, E_{\mathrm{T}}^{\mathrm{miss}})))}$;
- the scalar sum H_{T} of the transverse momenta of τ lepton candidates and the two highest momentum jets in the events: $H_{\mathrm{T}} = \sum p_{\mathrm{T}}^{\tau} + \sum_{i=1,2} p_{\mathrm{T}}^{\mathrm{jet}_i}$;
- the effective mass $m_{\mathrm{eff}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}}$.

give the correct response for the energy deposited in electromagnetic showers, although it does not correct for the lower response of the calorimeter to hadrons.

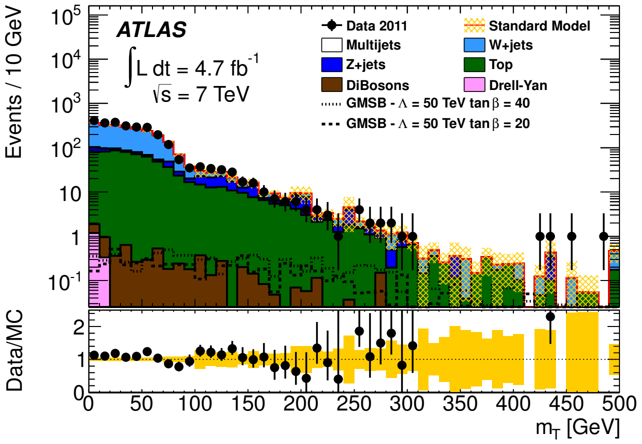
For each of the four final states, specific criteria are applied to the above quantities in order to define a signal region (SR), as summarized in Table 1.

Figure 1 shows the m_{T} and $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$ distributions for the 1τ and 2τ channels after all the requirements of the analysis except the final requirement on H_{T}. Similarly, Figure 2 shows the $m_{\mathrm{T}}^{e,\mu}$ distributions for the $\tau+\mu$ and $\tau+e$ channels after all the requirements of the analysis except the final m_{eff} requirement.

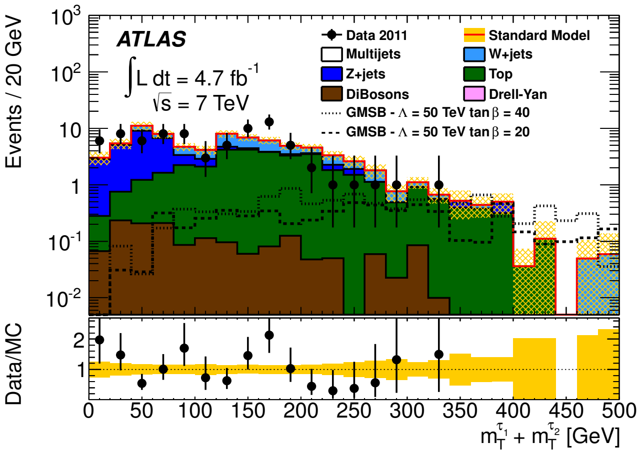
Figure 3 and 4 show the H_{T} distributions in the 1τ and 2τ channels, and m_{eff} distributions in the $\tau+\mu$ and $\tau+e$ channels, respectively, after all other selection criteria have been imposed.

6 Background estimation

The SM background expectation predicted by simulation in the SR is corrected by means of control regions (CRs), which are chosen such that a specific background process is enriched while any overlap with the SR is avoided. Data/MC comparison in the CRs show that MC overestimates the number of events compared to data, mainly due to mis-modelling of τ mis-identification probabilities and kinematics. Scaling factors are therefore obtained from the ratio of the number of observed events to the number of simulated background events in the control region where a given background contribution is enriched. Studies comparing data with MC simulations show that the τ mis-identification probability is, to a good approximation, independent of the kinematic variables used to separate the SR from the CRs, so that the measured ratio of the data to MC event yields in the CR can be used to compute scaling

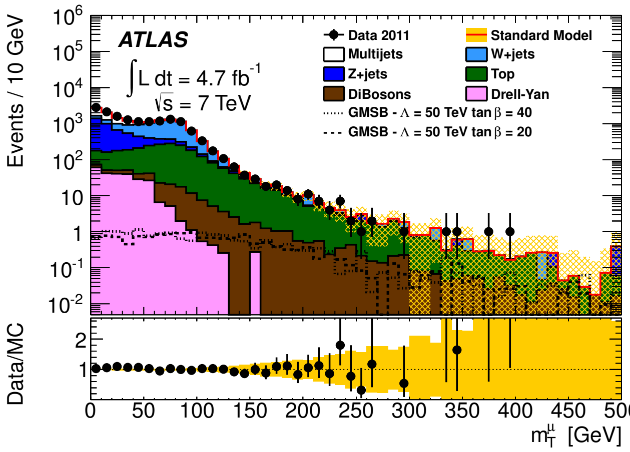


(a) m_{T} distribution for the 1τ final state.

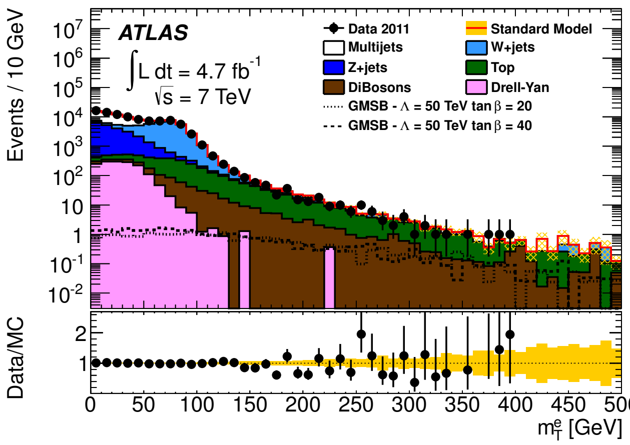


(b) $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$ distribution for the 2τ final state.

Fig. 1 Distribution of (a) m_{T} and (b) $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$ for the 1τ and 2τ final states, respectively, after all analysis requirements but the final requirement on H_{T}. Data are represented by the points, with statistical uncertainty only. The SM prediction includes the data-driven corrections discussed in the text. The band centred around the total SM background indicates the uncertainty due to finite MC sample sizes on the background expectation. Also shown is the expected signal from two typical GMSB samples ($\Lambda = 50\,\mathrm{TeV}, \tan\beta = 40$, $\Lambda = 50\,\mathrm{TeV}, \tan\beta = 20$).



(a) m_{T}^{μ} distribution for the τ+μ final state.



(b) m_{T}^{e} distribution for the τ+e final state.

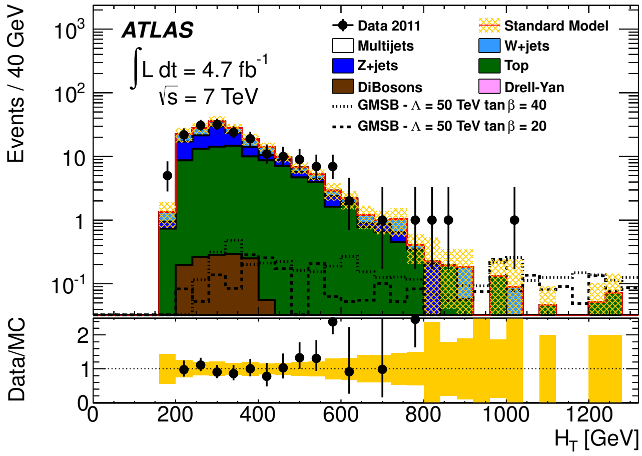
Fig. 2 Distribution of $m_{\mathrm{T}}^{e,\,\mu}$ for the (a) τ+μ and (b) τ+e final states after all analysis requirements but the final requirement on m_{eff}. Data are represented by the points, with statistical uncertainty only. The SM prediction includes the data-driven corrections discussed in the text. The band centred around the total SM background indicates the uncertainty due to finite MC sample sizes on the background expectation. Also shown is the expected signal from two typical GMSB samples ($\Lambda = 50\,\mathrm{TeV}, \tan\beta = 40$, $\Lambda = 50\,\mathrm{TeV}, \tan\beta = 20$).

factors to correct the MC background prediction in the SR.

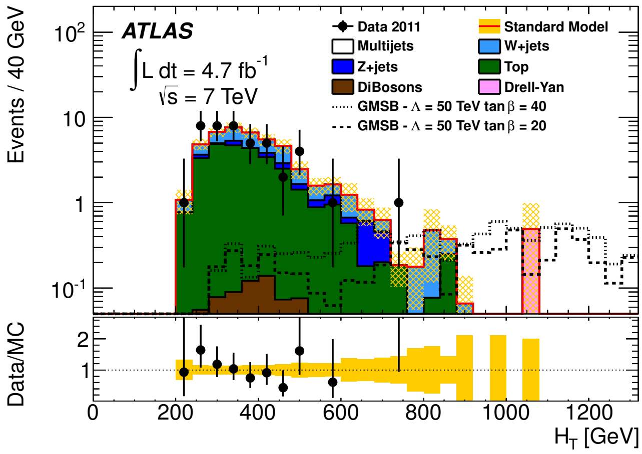
The dominant background contributions in the SR arise from top quark pair and single top events (hereafter generically indicated as 'top'), W+jets, Z+jets and multi-jet events. The latter background does not contribute significantly to the τ+μ final state. The CR definitions used to estimate these background contributions in the various channels are summarized in Table 2.

6.1 Background estimation in the 2τ channel

The W and top background contributions are dominated by events in which one τ candidate is a true τ and the others are mis-reconstructed from hadronic activity in the final state. The background from Z+jets events is dominated by final states with $Z \to \tau\tau$ decays. The CRs defined for the estimation of these background contributions have a very small contamination from multi-jet events due to the requirement on $\Delta(\phi_{\mathrm{jet}_{1,2}-\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}})$ and the presence of two or more τ leptons. The signal contribution in these CRs is expected to be at less than 0.1 % for the models considered. Correlations between differ-

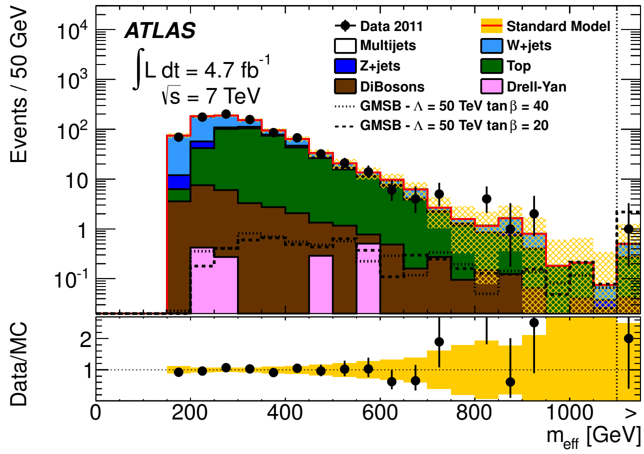


(a) H_{T} distribution for the 1τ final state.

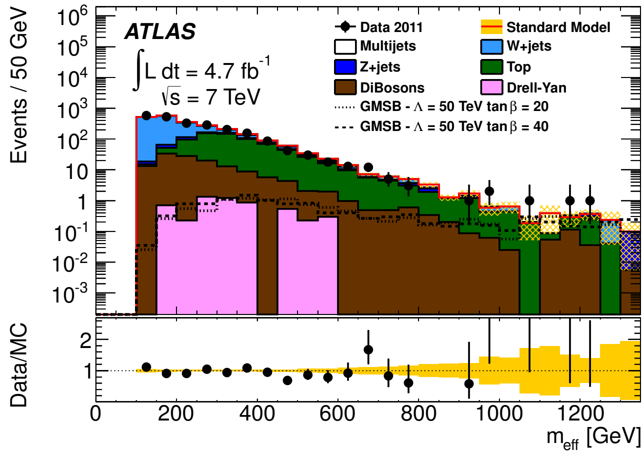


(b) H_{T} distribution for the 2τ final state.

Fig. 3 Distribution of H_{T} for the (a) 1τ and (b) 2τ final states after all analysis requirements. Data are represented by the points, with statistical uncertainty only. The SM prediction includes the data-driven corrections discussed in the text. The band centred around the total SM background indicates the uncertainty due to finite MC sample sizes on the background expectation. Also shown is the expected signal from two typical GMSB samples ($\Lambda = 50\,\mathrm{TeV}, \tan\beta = 40$, $\Lambda = 50\,\mathrm{TeV}, \tan\beta = 20$).



(a) m_{eff} distribution for the $\tau+\mu$ final state.



(b) m_{eff} distribution for the $\tau+e$ final state.

Fig. 4 Distribution of m_{eff} for the (a) $\tau+\mu$ and (b) $\tau+e$ final states after all analysis requirements. Data are represented by the points, with statistical uncertainty only. The SM prediction includes the data-driven corrections discussed in the text. The band centred around the total SM background indicates the uncertainty due to finite MC sample sizes on the background expectation. Also shown is the expected signal from two typical GMSB samples ($\Lambda = 50\,\mathrm{TeV}, \tan\beta = 40$, $\Lambda = 50\,\mathrm{TeV}, \tan\beta = 20$). In the top figure, the event in data surviving all the analysis requirements is shown in the overflow bin.

ent samples in the various CRs are taken into account by considering the matrix equation $\mathbf{N}^{\mathrm{data}} = A\,\boldsymbol{\omega}$, where $\mathbf{N}^{\mathrm{data}}$ is the observed number of data events in each of the CRs defined in Table 2, after subtracting the expected number of multi-jet events and any remaining sub-dominant background contribution, obtained from MC simulation. The matrix A is obtained from the MC expectation for the number of events originating from each of the background contributions (top, W and Z). The vector $\boldsymbol{\omega}$ of scaling factors is then computed by inverting the matrix A. To obtain the uncertainties for the scaling factors, all contributing parameters are varied according to their uncertainties, the procedure is repeated and new scaling factors are obtained. The width of the distribution of each resulting scaling factor is used as its uncertainty. The typical scaling factors obtained with this procedure are between 0.75 and 1 , with uncertainty of order 40 %. The multi-jet background expectation is computed in a multi-jet-dominated CR defined by inverting the $\Delta(\phi_{\mathrm{jet}_{1,2}-\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}})$ requirement and not applying the $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$ and H_{T} selection. In addition, an upper limit is imposed on the ratio $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ to increase the purity of this CR sample.

6.2 Background estimation in the 1τ channel

The number of events from W+jets and WZ processes in the SR is estimated by scaling the number of corresponding MC events with the ratio of data to MC events in the W+jets CR. The corresponding scaling factors are computed separately for the cases in which the τ candidates from W/top decays are true τ leptons and for those in which they are mis-reconstructed from hadronic activity in the final state. It has been checked that the same scaling factors can be applied to both W+jets and WZ processes. In the case of W+jets background events with true τ candidates, the charge asymmetry method [66, 67] is used. To estimate the background from top events with true τ candidates, a scaling-factor-based-technique is also used, where the number of b-tagged events in data in the top CR is fitted to a template from MC simulation ('template fit'). For background events in both W/top processes due to fake τ candidates, the matrix method already discussed for the 2τ background estimation is employed, where the parameters in the vector $\boldsymbol{\omega}$ of scaling factors are $\omega_W^{\rm fake}$, $\omega_W^{\rm true}$, $\omega_{\rm top}^{\rm fake}$ and $\omega_{\rm top}^{\rm true}$. The region dominated by fake τ candidates is defined by $m_{\rm T} > 110\,{\rm GeV}$ and $H_{\rm T} < 600\,{\rm GeV}$, while the one dominated by true τ candidates is defined by requiring $m_{\rm T} < 70\,{\rm GeV}$. The values of $\omega_{\rm top}^{\rm true}$ obtained from this method and from the template fit are in very good agreement. The factor $\omega_W^{\rm true}$ obtained with the charge asymmetry method agrees within 2σ with the one obtained with the matrix inversion method. The difference between the two $\omega_W^{\rm true}$ values is then assigned as a systematic uncertainty on the W+jets background estimation procedure. The background from Z+jets events is due to events where the Z decays to a pair of neutrinos, and contributes fully to the observed $E_{\rm T}^{\rm miss}$. The background contribution in the SR is estimated from data by measuring the data/MC ratio from $Z \to \ell^+\ell^-$ decays in the Z+jets CR defined in Table 2. Typical scaling factors are between 0.75 and 1.2 , with uncertainty of order 20 %. The multi-jet background expectation is computed in the same way as in the 2τ channel.

6.3 Background estimation in the $\tau+\mu$ and $\tau+e$ channels

The top background contribution consists of events where the muon (electron) candidate is a true muon (electron), and the τ candidate can either be a true τ or a hadronic jet mis-identified as a τ. On the other hand, the W+jets background consists mainly of events where the τ candidate is mis-reconstructed from hadronic activity in the final state. For this reason, the top CR is divided into two subregions: one dominated by true τ candidates, defined by $100\,{\rm GeV} < m_{\rm T}^{e,\mu} < 150\,{\rm GeV}$, and one dominated by fake ones ($50\,{\rm GeV} < m_{\rm T}^{e,\mu} < 100\,{\rm GeV}$). The same matrix approach already described is then used to estimate the true/fake top and W+jets background contributions to the SR. The scaling factors obtained are about 0.6–0.8 , with typical uncertainty of 15 %. The Z+jets background is much smaller than the W+jets one, and it is estimated using MC simulated events. The multi-jet background arises from mis-identified prompt leptons. By comparing the rates of events with and without the lepton isolation requirement, a data-driven estimate is obtained following the method described in Ref. [64].

The contribution from other sources of background considered (Drell-Yan and diboson events) is estimated in all analyses using directly the MC normalizations, without applying any further scaling factor.

Table 3 summarizes the estimated numbers of background events in the SR for each channel.

7 Systematic uncertainties on the background

Various systematic uncertainties were studied and the effect on the number of expected background events in each channel presented was evaluated, following the approach of Refs. [21, 22]. The dominant systematic uncertainties in the different channels are summarized in Table 4.

The theoretical uncertainty on the MC-based corrected extrapolation of the W+jets and top backgrounds from the CR into the SR is estimated using alternative MC samples. These MC samples were obtained by varying the renormalization and factorisation scales, the functional form of the factorisation scale and the matching threshold in the parton shower process in the generators used for the simulation of the events described in section 3.

Systematic uncertainties on the jet energy scale (JES) and jet energy resolution (JER) [57] are applied in MC events to the selected jets and propagated throughout the analysis. The difference in the number of expected background events obtained with the nominal MC simulation after applying these changes is taken as the systematic uncertainty.

The effect of the τ energy scale (TES) uncertainty on the expected background is estimated in a similar way. The uncertainties from the jet and τ energy scale are treated as fully correlated.

The uncertainties on the background estimation due to the τ identification efficiency depend on the τ identification algorithm ("loose" or "medium"), the kinemat-

Table 3 Number of expected background events and data yields in the four final states discussed. Where possible, the uncertainties are separated into statistical and systematic parts. The SM prediction is computed taking into account correlations between the different uncertainties. Also shown are the number of expected signal MC events for one GMSB point (Λ=50 TeV, $\tan\beta$=20), the 95 % confidence level (CL) upper limit on the number of observed (expected) signal events and corresponding cross-section from any new physics scenario that can be set for each of the four final states, taking into account the observed events in the data and the background expectations.

–	1τ	2τ	$\tau+\mu$	$\tau+e$
Multi-jet	$0.17 \pm 0.04 \pm 0.11$	$0.17 \pm 0.15 \pm 0.36$	$<\ 0.01$	0.22 ± 0.30
W + jets	$0.31 \pm 0.16 \pm 0.16$	$1.11 \pm 0.67 \pm 0.30$	$0.27 \pm 0.21 \pm 0.13$	$0.24 \pm 0.17 \pm 0.27$
Z + jets	$0.22 \pm 0.22 \pm 0.09$	$0.36 \pm 0.26 \pm 0.35$	$0.05 \pm 0.05 \pm 0.01$	$0.17 \pm 0.12 \pm 0.05$
Top	$0.61 \pm 0.25 \pm 0.11$	$0.76 \pm 0.31 \pm 0.31$	$0.36 \pm 0.18 \pm 0.26$	$1.41 \pm 0.27 \pm 0.84$
Diboson	$<\ 0.05$	$0.02 \pm 0.01 \pm 0.07$	$0.11 \pm 0.04 \pm 0.02$	$0.26 \pm 0.12 \pm 0.11$
Drell-Yan	$<\ 0.36$	$0.49 \pm 0.49 \pm 0.21$	$<\ 0.002$	$<\ 0.002$
Total background	$1.31 \pm 0.37 \pm 0.65$	$2.91 \pm 0.89 \pm 0.76$	$0.79 \pm 0.28 \pm 0.39$	$2.31 \pm 0.40 \pm 1.40$
Signal MC Events ($\Lambda = 50\,\text{TeV}, \tan\beta = 20$)	$2.36 \pm 0.30 \pm 0.60$	$4.94 \pm 0.45 \pm 0.74$	$2.48 \pm 0.30 \pm 0.39$	$4.21 \pm 0.38 \pm 0.46$
Data	4	1	1	3
Obs. (exp.) upper limit on number of signal events	7.7 (4.5)	3.2 (4.7)	3.7 (3.4)	5.2 (4.6)
Obs. (exp.) upper limit on visible Cross-Section (fb)	1.67 (0.95)	0.68 (0.99)	0.78 (0.72)	1.10 (0.98)

ics of the τ sample and the number of associated tracks. In the different channels, they vary between 2–5 %.

A systematic uncertainty associated with the simulation of pile-up in the MC events is also taken into account, with uncertainties varying between 5–20 %.

The effect of the 1.8 % uncertainty on the luminosity measurement [26, 27] is also considered on the normalization of the background contributions for which scale factors derived from CR regions were not applied (Drell-Yan and diboson in all channels, and Z+jets in the $\tau+\mu$ and $\tau+e$ channels).

The total systematic uncertainties obtained in the 1τ, 2τ, $\tau+\mu$ and $\tau+e$ channels are 52 %, 26 %, 49 % and 60 %, respectively. The limited size of the MC samples used for background estimation gives rise to a statistical error ranging from 21 % in the 1τ channel to 46 % in the $\tau+e$ channel.

8 Signal efficiencies and systematic uncertainties

The GMSB signal samples are described in Section 3. The total cross-section drops from 100 pb for $\Lambda = 15$ TeV to 5.0 fb for $\Lambda = 80$ TeV. The cross-section for strong production, for which this analysis has the largest efficiency, decreases faster than the cross-sections for slepton and gaugino production, such that for large values of Λ the selection efficiency with respect to the total SUSY production decreases. For the different final states, in the $\tilde{\tau}_1$ NLSP region the efficiency is about 3 % for the 2τ channel, 1 % for the $\tau+\mu$ and $\tau+e$ channels, and 0.5 % for the 1τ channel. In the non-$\tilde{\tau}_1$ NLSP regions and for high Λ values it drops to 0.1–0.2 % for all final states. The total systematic uncertainty on the signal selection from the various sources discussed in Section 7 ranges between 10–15 % for the 1τ channel, 15–18 % for the 2τ channel, 8–16 % for the $\tau+\mu$ channel and 11–17 % for the $\tau+e$ channel over the GMSB signal grid.

Theoretical uncertainties related to the GMSB cross-section predictions are obtained using the same procedure as detailed in Ref. [22]. These uncertainties are calculated for individual SUSY production processes and for each model point in the GMSB grid, leading to overall theoretical cross-section uncertainties between 5 % and 25 %.

9 Results

Table 3 summarizes the number of observed data events and the number of expected background events in the four channels, with separate statistical and systematic uncertainties. No significant excess is observed in any of the four signal regions. From the numbers of observed data events and expected background events, upper limits at 95 % confidence level (CL) of 7.7, 3.2, 3.7 and 5.2 signal events from any scenario of physics beyond the SM are calculated in the 1τ, 2τ, $\tau+\mu$ and $\tau+e$

Table 4 Overview of the major systematic uncertainties and the MC statistical uncertainty for the background estimates in the four channels presented in this paper.

Source of Uncertainty	1τ	2τ	$\tau+\mu$	$\tau+e$
CR to SR Extrapolation	27 %	12 %	26 %	29 %
Jet Energy Resolution	21 %	6.5 %	5.4 %	13 %
Jet Energy Scale	20 %	4.8 %	11 %	8.5 %
τ Energy Scale	10 %	8.5 %	0.3 %	4.3 %
Pile-up modelling	5.1 %	14 %	20 %	3.5 %
MC statistics	21 %	32 %	39 %	46 %

channels, respectively. Using only the background predictions, expected limits of 4.5, 4.7, 3.4 and 4.6 events are obtained for the four channels (1τ, 2τ, $\tau+\mu$ and $\tau+e$). The limits on the number of signal events are computed using the profile likelihood method [68] and the CL_s criterion [69]. Uncertainties on the background and signal expectations are treated as Gaussian-distributed nuisance parameters in the likelihood fit. The signal-event upper limits translate into a 95 % CL observed (expected) upper limit on the visible cross-section for new phenomena for each of the four final states, defined by the product of cross-section, branching fraction, acceptance and efficiency for the selections defined in Section 5. The results are summarized in Table 3 for all channels. In order to produce the strongest possible 95 % CL limit on the GMSB model parameters Λ and $\tan\beta$, a statistical combination of the four channels is performed. The likelihood function representing the outcome of the combination includes the statistical independence of the four final states considered. The resulting observed and expected lower limits for the combination of the four final states are shown in Figure 5. These limits are calculated including all experimental and theoretical uncertainties on the background and signal expectations. Excluding the theoretical uncertainties on the signal cross-section from the limit calculation has a negligible effect on the limits obtained. Figure 5 also includes the limits from OPAL [25] for comparison. The best exclusion from the combination of all final states is obtained for $\Lambda = 58$ TeV for values of $\tan\beta$ between 45 and 55 . The results extend previous limits and values of $\Lambda < 54$ TeV are now excluded at 95 % CL, in the regions where the $\tilde{\tau}_1$ is the next-to-lightest SUSY particle ($\tan\beta > 20$).

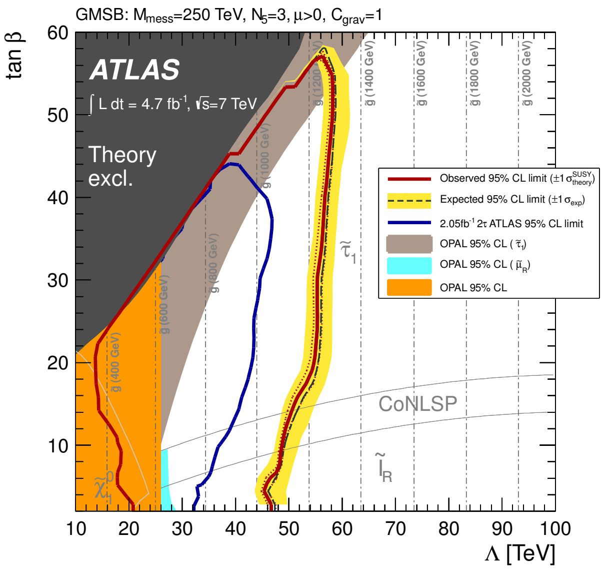


Fig. 5 Expected and observed 95 % CL lower limits on the minimal GMSB model parameters Λ and $\tan\beta$. The dark grey area indicates the region which is theoretically excluded due to unphysical sparticle mass values. The different NLSP regions are indicated. In the CoNLSP region the $\tilde{\tau}_1$ and the $\tilde{\ell}_R$ are the NLSPs. Additional model parameters are $M_{\mathrm{mess}} = 250$ TeV, $N_5 = 3$, $\mu > 0$ and $C_{\mathrm{grav}} = 1$. The limits from the OPAL experiment [25] are shown for comparison. The recent ATLAS limit [22] obtained on a subset (2 fb^{-1}) of the 2011 data in the 2τ final state is also shown.

10 Conclusions

A search for SUSY in final states with jets, $E_{\mathrm{T}}^{\mathrm{miss}}$, light leptons (e/$\mu$) and hadronically decaying τ leptons is performed using 4.7 fb^{-1} of $\sqrt{s} = 7$ TeV pp collision data recorded with the ATLAS detector at the LHC. In the four final states studied, no significant excess is found above the expected SM backgrounds. The results are used to set model-independent 95 % CL upper limits on the number of signal events from new phenomena and corresponding upper limits on the visible cross-section for the four different final states. Limits on the model parameters are set for a minimal GMSB model. A lower limit on the SUSY breaking scale Λ of 54 TeV is determined in the regions where the $\tilde{\tau}_1$ is the next-to-lightest SUSY particle ($\tan\beta > 20$) by statistically combining the result of the four analyses described in this paper. The limit on Λ increases to 58 TeV for $\tan\beta$ between 45 and 55 . These results provide the most stringent test to date of GMSB SUSY breaking models in a large part of the parameter space considered.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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