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Search for events with large missing transverse momentum, jets, and at least two tau leptons in 7 TeV proton–proton collision data with the ATLAS detector ☆

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ABSTRACT

A search for events with large missing transverse momentum, jets, and at least two tau leptons has been performed using 2 fb^{-1} of proton–proton collision data at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector at the Large Hadron Collider. No excess above the Standard Model background expectation is observed and a 95% CL upper limit on the visible cross section for new phenomena is set, where the visible cross section is defined by the product of cross section, branching fraction, detector acceptance and event selection efficiency. A 95% CL lower limit of 32 TeV is set on the gauge-mediated supersymmetry breaking (GMSB) scale Λ independent of $\tan\beta$. These limits provide the most stringent tests to date in a large part of the considered parameter space.

1. Introduction

Supersymmetry (SUSY) [1–5] 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. As none of these sparticles have been observed, SUSY must be a broken symmetry if realised in nature. Assuming R-parity conservation [6,7], sparticles are produced in pairs. These would then decay through cascades involving other sparticles until the lightest SUSY particle (LSP) is produced, which is stable.

Minimal gauge-mediated supersymmetry breaking (GMSB) [8–13] models can be described by six parameters: the SUSY breaking mass scale felt by the low-energy sector (Λ), the messenger mass (M_{mess}), the number of SU(5) messengers (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}). In this analysis Λ and $\tan\beta$ are treated as free parameters and the other parameters are fixed to $M_{\text{mess}} = 250$ TeV, $N_5 = 3$, $\mu > 0$ and $C_{\text{grav}} = 1$, similar to other GMSB benchmark points in the literature, e.g. G2a [14] and SPS7 [15]. The C_{grav} parameter determines the lifetime of the next-to-lightest SUSY particle (NLSP). For $C_{\text{grav}} = 1$ the NLSP decays promptly ($c\tau_{\text{NLSP}} < 0.1$ mm). With these parameters, the production of squark and/or gluino pairs is expected to dominate at the present Large Hadron Collider (LHC) energy. These sparticles decay directly or through cascades into the NLSP, which subsequently decays to the LSP. In GMSB models, the LSP is the very light gravitino ($\tilde{G}$). Due to the gravitino's very small mass of $\mathcal{O}$(keV), the NLSP is the only sparticle decaying into the LSP. This leads to multiple jets and missing transverse momentum ($E_{\text{T}}^{\text{miss}}$) in the final states. The experimental signature is then largely determined by the nature of the NLSP, which 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 ($\tilde{\nu}$), leading to final states containing taus, light leptons ($\ell = e, \mu$), photons, b-jets, or neutrinos. For $N_5 = 3$ the $\tilde{\tau}_1$ and $\tilde{\ell}_R$ NLSPs become more dominant compared to lower values of N_5. 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 between two and four tau leptons. In the so-called CoNLSP [16] region, the mass difference between the $\tilde{\tau}_1$ and the $\tilde{\ell}_R$ is smaller than the tau lepton mass such that both sparticles decay directly into the LSP and are therefore NLSP.

This Letter reports on the search for events with large $E_{\text{T}}^{\text{miss}}$, jets, and at least two hadronically decaying tau leptons. The analysis has been performed using 2 fb^{-1} of proton–proton (pp) collision data at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector at the LHC between March and August 2011. Although the analysis is sensitive to a wide variety of models for physics beyond the Standard Model, the results shown here are interpreted in the context of a minimal GMSB model. The three LEP Collaborations ALEPH [17], DELPHI [18] and OPAL [19] studied $\tilde{\tau}_1$ pair production, with the subsequent decay $\tilde{\tau}_1 \to \tau\tilde{G}$ in the minimal GMSB model. The best limits are set by the OPAL Collaboration and $\tilde{\tau}_1$ NLSPs with masses below 87.4 GeV are excluded. A limit on the SUSY breaking mass scale Λ of 26 TeV was set for $N_5 = 3$, $M_{\text{mess}} = 250$ TeV, independent of $\tan\beta$ and the NLSP lifetime. The CMS Collaboration searched for new physics in same-sign ditau events [20] and multi-lepton events including ditaus [21] using 35 pb^{-1} of data, but the minimal GMSB model was not considered. A search for supersymmetry in final states containing at least one hadronically decaying

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tau lepton, missing transverse momentum and jets with the ATLAS detector is presented in another Letter [22].

2. ATLAS detector

The ATLAS detector [23] is a multi-purpose apparatus 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 strip 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/scintillating-tile calorimeter provides hadronic coverage in the central rapidity[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

Monte Carlo (MC) simulations are used to extrapolate backgrounds from control regions (CRs) to the signal region (SR) and to evaluate the selection efficiencies for the SUSY models considered. Samples of W and Z/γ^* production with accompanying jets are simulated with ALPGEN [24], using CTEQ6L1 [25] parton density functions (PDFs). Top quark pair production, single top production and diboson pair production are simulated with MC@NLO [26–28] and the next-to-leading order (NLO) PDF set CTEQ6.6 [29]. Fragmentation and hadronisation are performed with HERWIG [30], using JIMMY [31] for the underlying event simulation and the ATLAS MC10 parameter tune [32]. TAUOLA [33,34] and PHOTOS [35] are used to model the decays of τ leptons and the radiation of photons, respectively. The production of multi-jet events is simulated with PYTHIA 6.4.25 [36] using the AMBT1 tune [37] and MRST2007 LO* [38] PDFs. For the minimal GMSB model considered in this analysis, the SUSY mass spectra are calculated using ISAJET 7.80 [39]. The MC signal samples are produced using HERWIG++ 2.4.2 [40] with MRST2007 LO* PDFs. NLO cross sections are calculated using PROSPINO 2.1 [41–46]. All samples are processed through the GEANT4-based simulation [47] of the ATLAS detector [48]. The variation of the number of pp interactions per bunch crossing (pile-up) as a function of the instantaneous luminosity is taken into account by modeling the simulated number of overlaid minimum bias events according to the observed distribution of the number of pile-up interactions in data, with an average of ~ 6 interactions.

4. Object reconstruction

Jets are reconstructed using the anti-k_t jet clustering algorithm [49] with radius parameter $R = 0.4$. Their energies are calibrated to correct for calorimeter non-compensation, upstream material and other effects [50]. Jets are required to have transverse momentum (p_{T}) above 20 GeV and $|\eta| < 2.5$.

Muons are identified as tracks in the ID matched to track segments in the stand-alone muon spectrometer, while electrons are identified as isolated tracks with a corresponding energy deposit in the electromagnetic calorimeter. The selection criteria applied to muons and "medium" quality electrons are described in more detail in Refs. [51] and [52], respectively.

The measurement of the missing transverse momentum two-dimensional vector $p_{\mathrm{T}}^{\mathrm{miss}}$ (and its magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) is based on the transverse momenta of identified jets, electrons, muons and all calorimeter clusters with $|\eta| < 4.5$ not associated to such objects [53]. For the purpose of the measurement of $E_{\mathrm{T}}^{\mathrm{miss}}$, taus are not distinguished from jets.

In this search, only hadronically decaying taus are considered. The tau reconstruction is seeded from anti-k_t jets with $p_{\mathrm{T}} > 10$ GeV. An η- and p_{T}-dependent energy calibration to the hadronic tau energy scale is applied. Hadronic tau identification is based on observables sensitive to the transverse and longitudinal shape of the calorimeter shower and on tracking information, combined in a boosted decision tree (BDT) discriminator [54]. Transition radiation and calorimeter information is used to veto electrons misidentified as taus. A tau candidate must have $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$, and one or three associated tracks of $p_{\mathrm{T}} > 1$ GeV with a charge sum of ± 1. The efficiency of the BDT tau identification (the "loose" working point in Ref. [54]), determined using $Z \to \tau\tau$ events, is about 60%, independent of p_{T}, with a jet background rejection factor of 20–50.

During a part of the data-taking period, an electronics failure in the LAr barrel EM calorimeter created a dead region in the second and third layers, corresponding to approximately 1.4×0.2 radians in $\Delta\eta \times \Delta\phi$. Electron and tau candidates falling in this region are discarded. A correction to the jet energy is made using the energy depositions in the cells neighbouring the dead region; events having at least one jet for which the energy after correction is above 30 GeV are discarded, resulting in a loss of $\sim 6\%$ of the data sample.

5. Data analysis

The analysed data sample, after applying beam, detector and data-quality requirements, corresponds to an integrated luminosity of (2.05 ± 0.08) fb^{-1} [55,56]. Candidate events are pre-selected by a trigger requiring a leading jet, i.e. the jet having the highest transverse momentum of all jets in the event, with $p_{\mathrm{T}} >$ 75 GeV, measured at the raw electromagnetic scale, and $E_{\mathrm{T}}^{\mathrm{miss}} >$ 45 GeV [57]. In the offline analysis, these events are required to have a reconstructed primary vertex with at least five tracks, a leading jet with $p_{\mathrm{T}} > 130$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV. These requirements ensure a uniform trigger efficiency that exceeds 98%.

Pre-selected events are then required to have at least two identified tau candidates and must not contain any electron or muon candidates with transverse momenta above 20 GeV or 10 GeV, respectively. To suppress soft multi-jet events, a second jet with $p_{\mathrm{T}} > 30$ GeV is required. The p_{T} spectrum of the leading tau candidate after pre-selection of candidate events, soft multi-jet rejection and the requirement of two or more taus and no light leptons is shown in Fig. 1.

This selection rejects almost all soft multi-jet background events. Remaining multi-jet events, where highly energetic jets are mis-measured, are rejected by requiring the azimuthal angle between the missing transverse momentum and either of the two leading jets $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}_{1,2})$ to be larger than 0.4 radians.

The SR is defined by requiring $m_{\mathrm{eff}} > 700$ GeV and $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2} >$ 80 GeV, where m_{eff} is the effective mass[2] and $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$ is the

[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 $\eta = -\ln\tan(\theta/2)$.

[2] The effective mass m_{eff} is calculated as the sum of $E_{\mathrm{T}}^{\mathrm{miss}}$ and the magnitude of the transverse momenta of the two highest-p_{T} jets and all selected taus.

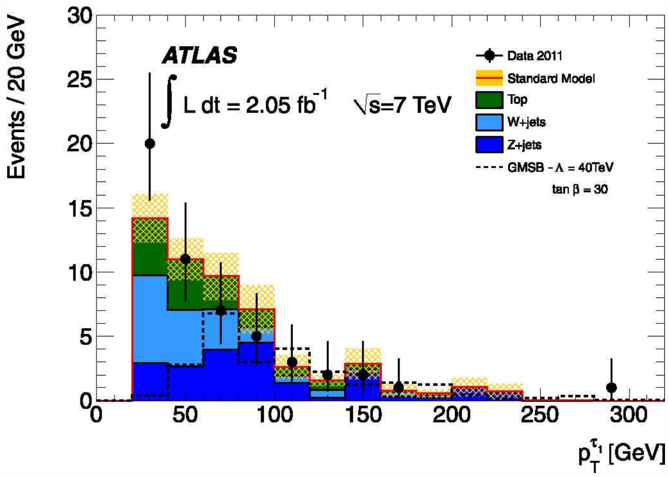


Fig. 1. The p_{T} spectrum of the leading tau candidates in data (points, statistical uncertainty only) and the estimated SM background after the pre-selection of candidate events, soft multi-jet rejection and the requirement of two or more taus and no light leptons. The band centred around the total SM background indicates the statistical uncertainty. Also shown is the expected signal from a typical GMSB ($\Lambda = 40$ TeV, $\tan\beta = 30$) sample.

sum of the transverse masses[3] of the two leading tau candidates. The m_{eff} distribution after the $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet}_{1,2})$ requirement and the $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$ distribution after the m_{eff} requirement are shown in Fig. 2. After applying all the analysis requirements, 3 events are selected in the data.

6. Background estimation

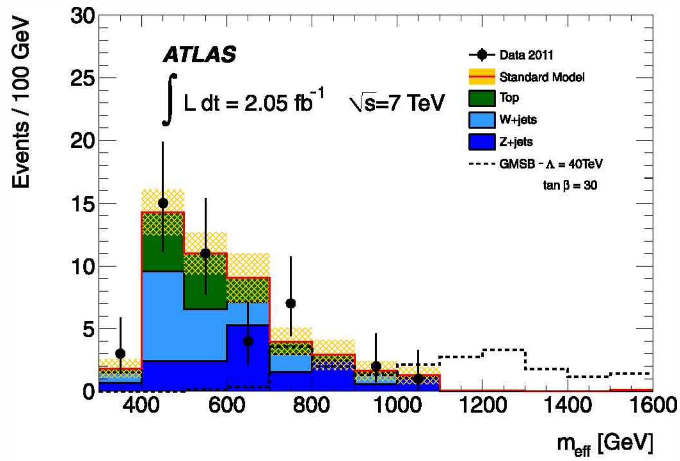
The dominant backgrounds in the SR arise from top-pair plus single top events (here generically indicated as $t\bar{t}$), $W \to \tau\nu_\tau$ events and $Z \to \tau\tau$ events. While the latter comprises final states with two true taus, which are well described in the simulation, the W and $t\bar{t}$ background consist of events in which one real tau is correctly reconstructed and the other tau candidates are mis-reconstructed from hadronic activity in the final state. Since mis-identified taus are not well described in the MC, the background contribution from $t\bar{t}$ and $W \to \tau\nu_\tau$ is determined simultaneously in a CR defined by inverting the m_{eff} cut. Owing to the requirement on $\Delta\phi$ and of two or more taus, this CR has negligible contamination from multi-jet events. Moreover, a totally negligible contribution is expected in this CR from signal events. The MC overestimates the number of events in the CR compared to data, due to mis-modeling of tau misidentification probabilities. MC studies show that the tau misidentification probability is, to a good approximation, independent of m_{eff}, so that the measured ratio of the data to MC event yields in the CR can be used to correct the MC background prediction in the SR.

In a similar way, the multi-jet background expectation is computed in a multi-jet dominated CR defined by inverting the $\Delta\phi$ and m_{eff} cuts. In addition, $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}} < 0.4$ is required to increase the purity of this CR sample. The extrapolated contribution of this background source to the SR is found to be negligible.

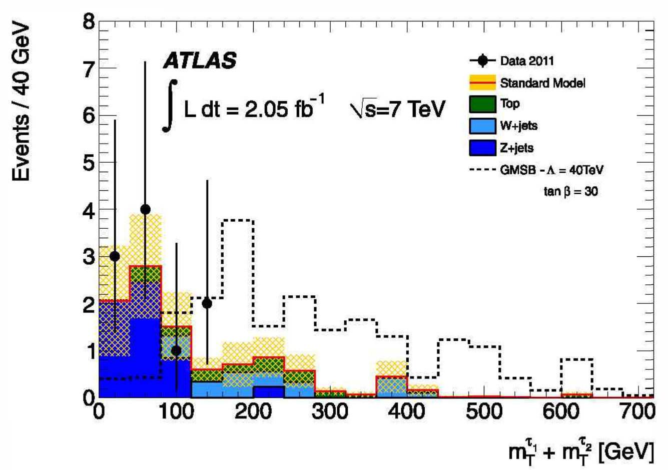
7. Systematic uncertainties on the background

The theoretical uncertainty on the MC-based corrected extrapolation of the W and $t\bar{t}$ backgrounds from the CR into the SR

[3] The transverse mass m_{T} formed by $E_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of the tau lepton (τ) is defined as $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos(\Delta\phi(\tau, p_{\mathrm{T}\,\mathrm{miss}})))}$.



(a) m_{eff} distribution after the $\Delta\phi$ requirement



(b) $m_{\mathrm{T}}^{\tau_1} + m_{\mathrm{T}}^{\tau_2}$ distribution after the m_{eff} requirement

Fig. 2. Distributions of variables used for the signal region definition in data (points, statistical uncertainty only) and the estimated SM background after the pre-selection of candidate events, soft multi-jet rejection and the requirement of two or more taus and no light leptons. The band centred around the total SM background indicates the statistical uncertainty. Also shown is the expected signal from a typical GMSB ($\Lambda = 40$ TeV, $\tan\beta = 30$) sample.

is estimated using alternative MC samples obtained by varying the renormalisation and factorisation scales, the functional form of the factorisation scale and the matching threshold in the parton shower process. An uncertainty of 14% is estimated from this procedure. Moreover, an uncertainty of 23% is associated to the normalisation factor derived in the CR. This uncertainty is estimated by repeating the normalisation to data independently for W and $t\bar{t}$. Systematic uncertainties on the jet energy scale and jet energy resolution [50] are applied in MC to the selected jets and propagated throughout the analysis, including to $E_{\mathrm{T}}^{\mathrm{miss}}$. 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 and corresponds to 18% each. The effect of the tau energy scale uncertainly on the expected background is estimated in a similar way and amounts to 7%. The uncertainties from the jet and tau energy scale are treated as fully correlated. The tau identification efficiency uncertainties on the background depends on the tau identification algorithm, the kinematics of the τ sample and the number of associated tracks. The systematic uncertainties associated to the tau identification and misidentification are found to be 2.5% and 0.5%, respectively. For the $t\bar{t}$ and W backgrounds, these uncertainties are absorbed into the normalisation. The systematic uncertainty associated to pile-up simulation in MC is 1%. The normalisation of the $Z+$jets and diboson backgrounds is affected by the uncertainty of 3.7% on the luminosity measurement [55,56]. This results in a 0.8% uncertainty on the total background. The contributions from the different systematic uncertainties result in a total background systematic uncertainty of 41%.

In total $5.3 \pm 1.3\,(\text{stat}) \pm 2.2\,(\text{sys})$ background events are expected where the first uncertainty is statistical and includes the statistical component of the background correction factor uncertainty and the second is systematic. Roughly half of the background is composed of $t\bar{t}$ events and the other half is evenly split into W and Z events with accompanying jets.

8. Signal efficiencies and systematic uncertainties

GMSB signal samples were generated on a grid ranging from $\Lambda = 10$ TeV to $\Lambda = 80$ TeV and from $\tan\beta = 2$ to $\tan\beta = 50$. The number of selected events decreases significantly with increasing Λ due to the reduced cross section. The cross section drops from 100 pb for $\Lambda = 15$ TeV to 5.0 fb for $\Lambda = 80$ TeV. The selection efficiency is highest ($\approx 3\%$) for high $\tan\beta$ and lower Λ values, including in the region of the GMSB4030 point ($\Lambda = 40$, $\tan\beta = 30$) which is near the expected limit. It drops to 0.2% in the non-$\tilde{\tau}_1$ NLSP regions and for high Λ values. This is primarily a consequence of the light lepton veto and the requirement of two hadronically decaying taus, respectively.

The total systematic uncertainty on the signal selection from the systematic uncertainties discussed in Section 7 ranges between 7.5% and 36% over the GMSB grid. The statistical uncertainty from the limited size of the MC signal samples is of the order of 20%, with variations between 7.6% and 59% at the edges of the accessible signal range. Theory uncertainties related to the GMSB cross section predictions are estimated through variations of the factorisation and renormalisation scales in the NLO PROSPINO calculation between half and twice their default values, by considering variations in α_s, and by considering PDF uncertainties using the CTEQ6.6M PDF error sets [58]. These uncertainties are calculated for individual SUSY production processes and for each model point, leading to overall theoretical cross section uncertainties between 6.5% and 22%. Altogether this yields $20.8 \pm 3.4\,(\text{stat}) \pm 3.6\,(\text{sys}) \pm 3.3\,(\text{theo})$ signal events for the GMSB4030 point.

9. Results

Based on the observation of 3 events in the SR and a background expectation of $5.3 \pm 1.3\,(\text{stat}) \pm 2.2\,(\text{sys})$ events, an upper limit of 5.9 (7.0) events observed (expected) is set at 95% Confidence Level (CL) on the number of events from any scenario of physics beyond the SM, using the profile likelihood and CL_s method [59]. Uncertainties on the background and signal expectations are treated as Gaussian-distributed nuisance parameters in the likelihood fit. This limit translates into a 95% observed (expected) upper limit of 2.9 fb (3.4 fb) on the visible cross section for new phenomena, defined by the product of cross section, branching fraction, acceptance and efficiency for the selections defined in Section 5. The resulting expected and observed 95% CL limits on the GMSB model parameters Λ and $\tan\beta$ are shown in Fig. 3, including the lower limits from OPAL [19] for comparison. 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

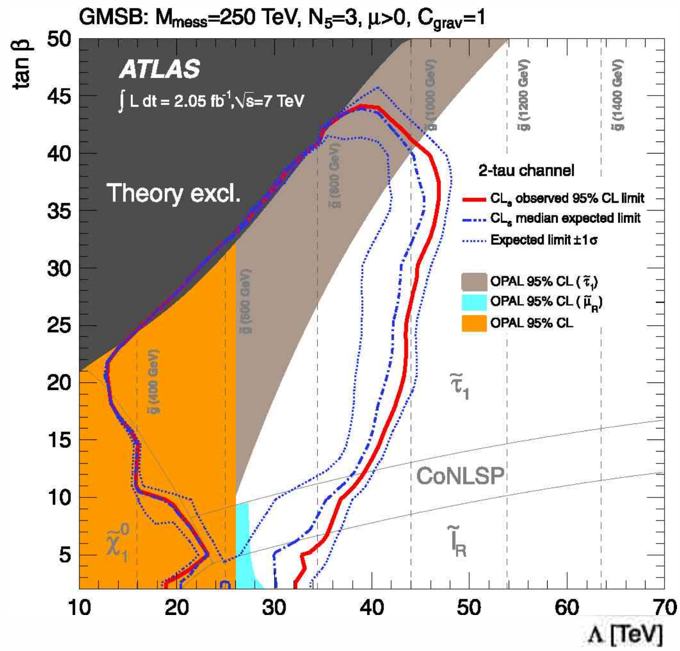


Fig. 3. Expected and observed 95% CL limits on the minimal GMSB model parameters Λ and $\tan\beta$. The dark grey area indicates the region which is theoretically excluded due to unphysical sparticle mass values. The different NLSP regions are indicate. In the CoNLSP region the $\tilde{\tau}_1$ and the $\tilde{\ell}_R$ are the NLSP. Additional model parameters are $M_{\text{mess}} = 250$ TeV, $N_5 = 3$, $\mu > 0$ and $C_{\text{grav}} = 1$. The previous OPAL [19] limits are also shown.

limit calculation has a negligible effect on the limits obtained. The best exclusion is set for $\Lambda = 47$ TeV and $\tan\beta = 37$. The results extend previous limits and values of $\Lambda < 32$ TeV are now excluded at 95% CL, independent of $\tan\beta$.

10. Conclusions

A search for events with two or more hadronically decaying tau leptons, large $E_{\text{T}}^{\text{miss}}$ and jets is performed using 2 fb^{-1} of $\sqrt{s} = 7$ TeV pp collision data recorded with the ATLAS detector at the LHC. Three events are found, consistent with the expected SM background. The results are used to set a model-independent 95% CL upper limit of 5.9 events from new phenomena, corresponding to an upper limit on the visible cross section of 2.9 fb. Limits on the model parameters are set for a minimal GMSB model. The limit on the SUSY breaking scale Λ of 32 TeV is determined, independent of $\tan\beta$. It increases up to 47 TeV for $\tan\beta = 37$. These results provide the most stringent tests in a large part of the parameter space considered to date, improving the previous best limits.

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